Critical Temperature of a Superconductor/Ferromagnet Nanostructure near a Magnetic Skyrmion

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Contact between a superconductor and a chiral ferromagnet containing complex magnetic structures (helical or conical texture, skyrmion, and chiral float) has been considered. The case of a single skyrmion has been studied more thoroughly. The influence of these magnetic inhomogeneities on the critical temperature becomes significant only for nanoscale spin structures (about 100 nm or smaller). Skyrmion lattices and single skyrmions of such sizes have recently been observed in experiments with thin magnetic layers. Within the proximity effect theory in the dirty limit, an approximate approach has been proposed to calculate the critical temperature in these systems. Great influence of nanoscale spin vortices on the critical temperature, in combination with topological stability and a low current density that is necessary for their motion, makes it possible to use these systems as efficient superconducting spin valves.

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Contact between a superconductor (S) and a ferromagnetic metal (F) is very attractive for investigations because of the possible coexistence of ferromagnetic and superconducting orders in the same sample [1–7]. The possibility of applying these systems in superconducting microelectronics was investigated theoretically and experimentally [8–10]. Cooper pairs penetrate into a uniform ferromagnetic layer at a relatively small depth of about $\sqrt{D_f I}$, where $D_f$ is the diffusion coefficient in the ferromagnet and $I$ is the effective exchange field. The exchange interaction of superconducting electrons with electrons in the magnet induces many interesting phenomena of practical importance. For example, much attention has recently been paid to the proximity effect between a superconductor and a chiral magnet, in which stable magnetic skyrmions may exist, in particular, because the authors of experimental studies [11–13] reported the observation of magnetic vortices with a size of several nanometers [14]. In contrast to magnetic microinhomogeneities, these magnetic structures significantly affect the thermodynamic and transport properties of S/F systems. For example, the proximity effect between a superconductor and a chiral ferromagnet in the helicoidal phase was discussed in [15, 16]. The influence of a superconductor on the skyrmion stability in an S/F system was considered in [17]. The possibility of the formation of an Abrikosov vortex in a superconductor against the background of a Néel-type skyrmion in a ferromagnetic layer with allowance for the spin–orbit interaction was studied in [18]. The skyrmion–vortex bound state was considered in [19], where it was shown that the vortex displacement relative to the skyrmion center is possible under certain conditions. The authors of [20] presented, among other results, the distribution of the superconducting current in an S/F/S system, containing a skyrmion, calculated by the finite element method. The theory of the proximity effect in S/F systems containing magnetic inhomogeneities was comprehensively developed in [1–3]; however, many three-dimensional problems are technically difficult. One of these problems is to calculate the critical temperature of the S/F system containing a magnetic vortex or a domain wall [21, 22]. In this work, we propose an approximate approach to such problems based on the transition to a new basis by a unitary transformation in the spin space of an itinerant electron. As shown in [23], this approach can be applied to a Hamiltonian in the effective exchange field approximation. In this study, we apply the unitary transformation to the Usadel equations obtained in [24] for magnetization nonuniform in direction. Furthermore, we consider superconductor and ferromagnet layers in the dirty limit, when the coherence lengths $\xi_s$ and $\xi_f$ in the superconductor and ferromagnet exceed significantly the corresponding mean free paths $l_s$ and $l_f$ [1, 3]. In this case, the Usadel equation for the ferromagnetic layer at an arbitrarily directed magnetization can be written as [24]

$$\frac{D_f}{2} \hat{\nabla}^2 \hat{F}(r, \omega) - i \sigma \hat{F}(r, \omega) = \frac{i}{2} \text{sgn}(\mathbf{t}, \hat{\sigma}) \hat{F}(r, \omega),$$

where $\hat{F}(r, \omega)$ is the fermion propagator, $D_f$ is the diffusion coefficient in the ferromagnet, $\sigma$ is the density of states, $\hat{\sigma}$ is the Pauli spin matrix, $\mathbf{t}$ is the magnetic field vector, and $\text{sgn}$ is the sign function.
\[
\begin{align*}
(I, \hat{\sigma}) &= \begin{pmatrix} \cos(\theta) & \sin(\theta) e^{-i\phi} \\ \sin(\theta) e^{i\phi} & -\cos(\theta) \end{pmatrix}, \\
\end{align*}
\]

where \( \hat{F} \) is the Usadel matrix function, \( D_r \) is the diffusion coefficient in the ferromagnetic layer, \( I \) is the effective exchange field, \( \omega \) is the Matsubara frequency, \( \Delta \) is the superconducting order parameter, and \( \theta \) and \( \phi \) are the polar and azimuthal angles, respectively, determining the magnetization direction. Hereinafter, it is accepted for simplicity that \( k_B = \mu_B = h = 1 \), where \( k_B \) is the Boltzmann constant, \( \mu_B \) is the Bohr magneton, and \( h \) is the reduced Planck constant.

Let us make a local rotation in the spin basis:

\[
\hat{F}(r, \omega) = \hat{U}^{-1} \tilde{F}(r, \omega) \hat{U},
\]

where \( \hat{U} \) is the unitary rotation matrix chosen so that \( \hat{U} (I, \hat{\sigma}) \hat{U}^{-1} = I \hat{\sigma}_3 \), having the form

\[
U = \begin{pmatrix}
\cos(\theta/2) e^{i\gamma} & \sin(\theta/2) e^{i(\gamma - \phi)} \\
-\sin(\theta/2) e^{-i(\gamma - \phi)} & \cos(\theta/2) e^{-i\gamma}
\end{pmatrix},
\]

where \( \gamma(r) \) is an arbitrary real function of coordinates. The arbitrariness of \( \gamma(r) \) corresponds to the invariance of the equation with respect to the local rotations around the \( z \) axis in the spin space of the itinerant electron. For the transformed Usadel matrix function \( \tilde{F} \), the equation can be written as

\[
\frac{D_r}{2} \Delta^2 \tilde{F}(r, \omega) - i|\sigma| \tilde{F}(r, \omega) \\
- \frac{iD_r}{2} \text{sgn} \omega [\tilde{F}(r, \omega), \hat{\sigma}_3] = 0.
\]

The extended derivative \( \tilde{D} \) is determined in this case as \( \tilde{D} \hat{f} = \tilde{D} \tilde{f} + [\hat{A}, \tilde{f}], \hat{A} = \tilde{U} \tilde{A} \tilde{U}^{-1} \). It has exactly the same form for the Green’s functions in Gor’kov equations. Using transformation (3), Eq. (1) can be reduced to Eq. (5) for an arbitrary dependence of the magnetization direction on coordinates. In the generalized Kupriyanov–Lukichev boundary conditions [25], the gradient is also replaced with the extended derivative. For example, we present the boundary conditions for a two-layer S/F system:

\[
\frac{4D_r}{v_s \sigma_f} (\nabla \tilde{F}_s, n) = \frac{4D_r}{v_t \sigma_f} (\tilde{D} \tilde{F}_t, n) = \tilde{F}_t - \tilde{F}_s,
\]

where \( v_{s(f)} \) is the Fermi velocity in the S (F) layer and \( \sigma_{s(f)} \) is the boundary transparency from the side of the S (F) layer [3]. In this case, the normal is directed from the S layer to the F layer. Note that, in the presence of two or more internal boundaries, rotations of the Usadel function in the form (3) may be needed to match the basis in the spin space. The free boundary conditions for the ferromagnet and superconductor have the form

\[
(\nabla \tilde{F}, n) = 0, \quad (\tilde{D} \tilde{F}, n) = 0.
\]

The boundary-value problem also includes the Usadel equation in the superconducting layer:

\[
\frac{D_r}{2} \nabla^2 \tilde{F}(r, \omega) - i|\sigma| \tilde{F}(r, \omega) = -\Delta_1 \hat{I}.
\]

The boundary-value problem should be supplemented with the self-consistency equation [1, 2]

\[
\Delta_1 \ln \left( \frac{T_c}{T_{cs}} \right) = \pi T_c \sum_{\omega_0 \neq 0} \text{Tr} [\tilde{F}(x, \omega) - \frac{\Delta_1}{\omega}],
\]

where \( T_{cs} \) is the critical temperature of a solitary superconductor and \( \omega_0 \) is the Debye frequency. The self-consistency equation is invariant under the unitary transformations of the function \( \tilde{F} \). The magnetic field produced by the ferromagnetic layer is not taken explicitly into account in Eqs. (1), (7), and (8). In the ferromagnetic layer, its contribution is small in comparison with the effective exchange field. The magnetic-field strength in the superconducting layer depends on the magnetization configuration in the entire sample (in particular, on the magnetization at a large distance from the contact region under consideration). Generally, the field generated by a fairly thin ferromagnetic film is weak, and according to most researchers (see, e.g., work [26] or reviews [1–3]), the critical temperature in the case of good metal contact is mainly affected by the penetration of Cooper pairs into the ferromagnet. However, it should be noted that the magnetic field plays a very important role when considering the bound state of the skyrmion and Abrikov vortex [18, 19]. Thus, contacts with type II superconductors in magnetic fields above \( H_{c1} \) are not described in our model.

Transformations (3) allow one to simplify significantly the boundary-value problem for many magnetic phases implemented in chiral magnets. In particular, if a ferromagnet is in the helicoidal phase, the wave vector of which is directed along the boundary, all components of the Usadel matrix function depend only on the distance from the boundary. In [24], this approach made it possible to calculate the Josephson current through the inhomogeneous ferromagnet layer. The critical temperature of the S/F system for this magnetization configuration was previously calculated in [15] using the method of fundamental solutions [27]. The critical temperature was considered at two different magnetic-helix orientations: along the boundary and perpendicular to it. The difference between the critical temperatures depended on the layer thicknesses, contact quality, and magnetic-helix period. It was shown that the critical temperature is higher in the case where the helix is oriented along the boundary. Our results for this system, presented below.
(see, e.g., lines 1 and 5 in Fig. 1), are in good agreement with the results of [15], which substantiate the use of the above-proposed method. Let us now try to find the critical temperature of the contact between the superconductor and the ferromagnet in the conical phase. The local unitary transformation, in combination with the arbitrarily chosen function $\gamma(r)$ in Eq. (4), makes it possible to reduce the boundary-value problem to a one-dimensional system of second-order equations with constant coefficients. Further calculations are carried out in a standard way in the approximation of the layer-constant order parameter [28–30]. It has become very popular because of the combination of simplicity and good consistency with a more rigorous method of fundamental solutions [27]. The Usadel function obtained is substituted into self-consistency equation (9), which is solved numerically.

We present the dependence of the critical temperature of a two-layer S/F system on the ferromagnet thickness for different magnetization orientations in the ferromagnet relative to the S/F interface. Along with the already analyzed cases of the magnetic helicoid with the wave vector directed along the normal to the S/F interface or lying in its plane [15], we considered the conical phase with a polar angle of $\pi/6$ (see Fig. 1).

The used parameters of the theory (chosen as an example) are close to the respective experimental quantities obtained in [31] for the contact between vanadium ($T_{cs} = 5.4$) and iron with a representative value of the effective exchange field $I$ on the order of 1000 K.

The calculation of the critical temperature of the S/F system with an arbitrary magnetization configuration is generally a much more complex problem. For the spin textures such as magnetic vortices and domain walls, Eq. (1) cannot be reduced to an equation with constant coefficients by transformation in the form (3). However, the phase of the transformed Usadel function changes along the S/F interface to a much lesser extent. The reason is that the phase of the components of the Usadel functions is mainly determined by the magnetization direction and the ferromagnetic layer thickness in this region of the interface. For the modified function $\tilde{F}(r, \omega)$, the magnetization direction is always identical by definition. As a result, we can apply an approximate approach to estimating the critical temperature of the system. The hierarchy of terms in Eq. (5) is rather complex. As a rule, the largest components are the term with the second derivative of the Usadel function (in the direction perpendicular to the boundary) and the expression containing the product of the effective exchange field and the Usadel function. For the terms that are most significant in the self-consistency equation and correspond to small Matsubara frequencies, the corresponding terms in Eq. (5) are also not very large. The other terms entering the extended derivative are corrections to the main terms for skyrmions implemented in practice. In this case, the change in the Usadel function in the interface plane is due to a change in these corrections from point to point. In view of the aforesaid, the corresponding gradients are fairly small, especially for large skyrmions ($r \gg \xi_s$). We can also suggest estimation from more general considerations, which is appropriate for small-scale magnetic vortices. The superconducting order parameter in the superconductor bulk may change significantly at distances exceeding the superconducting coherence length $\xi_s$. Then, according to the self-consistency equation and boundary conditions (7), the Usadel function in the ferromagnetic layer changes in magnitude in the interface plane with the same slow rate. In Eq. (5), we neglect derivatives of the Usadel function in the plane as values on the order of $1/\xi_s$. Here, we take into account that the phase changes in the interface plane were almost completely taken into consideration by the local unitary transformation (3). This quite rough approximation makes it possible to reduce Eq. (5) to a system of ordi-
nary differential equations. Let us now consider the quantity $\hat{A}$. In the general case, it has the form

$$\hat{A} = -\frac{i}{2}(\sin(2\gamma - \phi)\hat{\sigma}_1 + \cos(2\gamma - \phi)\hat{\sigma}_2)\nabla\theta + i\hat{\sigma}_3\left(\sin\frac{\theta}{2}\nabla\varphi - \nabla\gamma\right)$$

(10)

In view of the arbitrariness of the function $\gamma(r)$, this expression can be simplified. We set to zero the diagonal component of the effective tensor field

$$\hat{A} = -\frac{i}{2}\hat{\sigma}_1\nabla\theta + \frac{i\sin\theta}{2}\hat{\sigma}_2\nabla\varphi. \quad (11)$$

With allowance for Eq. (11), the divergence of the effective tensor field $\hat{A}$, entering the expression $D^2\tilde{F}(r,\omega)$, can be written as

$$\langle\nabla, \hat{A}\rangle = -\frac{i}{2}\hat{\sigma}_1\Delta\theta + \frac{i\sin\theta}{2}\hat{\sigma}_2\Delta\varphi + \frac{i\sin 2\theta}{4}\hat{\sigma}_3(\nabla\varphi)^2. \quad (13)$$

When solving the Usadel equation in the superconducting layer, it is also convenient to use the approximation of superconducting order parameter constant within the layer. These approximations allow us to split the problem into one-dimensional boundary-value problems for each pair of coordinates in the interface plane and solve them by a standard method for second-order systems with constant coefficients. When solving self-consistency equation (9) within this approach, we average the Usadel function in the S layer over the coordinate of the axis perpendicular to the interface and solve it numerically. In the interface plane, we average (smooth) the Usadel function with a Gaussian weight on the scale $\xi_s$, because the critical temperature of the superconducting transition cannot be determined on a smaller scale. In addition, the trace of the Usadel matrix function entering the self-consistency equation changes along the boundary very slowly. Despite the roughness of this approach, it is a way to qualitatively estimate the local influence of a magnetic vortex on the critical temperature. To determine the magnetization profile, we applied the method described in [13] for the experimentally observed small-scale single skyrmion. The dependence of the polar angle on the coordinate can be found from the equation

$$\theta_{\psi}'' + \frac{\theta_{\psi}'}{\rho} + \frac{2\sin^2\theta}{\rho} - \sin 2\theta\left(\frac{1}{\rho^2} + k\right) - h\sin\theta = 0; \quad \theta(0) = \pi; \quad \theta(\infty) = 0, \quad (14)$$

where $\rho = \frac{2\pi r}{L_D}$, $r$ is the distance to the skyrmion center, $L_D$ is the magnetic helicoid period in the absence of external field and anisotropy, and $k$ and $h$ are the parameters in the density functional of the micromagnetic energy (for details, see [13]). The behavior of the azimuthal angle depends on the skyrmion type. The skyrmion radius is determined as $\rho = \frac{\theta_0}{\theta_{\psi}}, \quad (15)$

where $(r_0, \theta_0)$ is the inflection point of the magnetization profile.

As one would expect, the influence of a magnetic inhomogeneity on the critical temperature near it is determined by its size in comparison with the superconducting coherence length. Figure 2 shows the dependence of the critical temperature of the superconductor near a single skyrmion, localized in the neighboring ferromagnetic layer, on the skyrmion radius at different S and F layer thicknesses. The described effect is very sensitive to the superconducting layer thickness and the interface transparency.

**Fig. 2.** (Color online) Critical temperature $T_c$ of the S/F system versus the radius $r$ of an isolated skyrmion at the parameters $l_s = 120$ Å, $\xi_s = 125$ Å, $2\pi r_s = 0.3$, $\sigma_s = 4$, and $n_f = 4$ and the thicknesses of the S and F layers (1) $d_s = 112$ Å, $d_f = 10$ Å and (2) $d_s = 100$ Å, $d_f = 25$ Å. Inset: $T_c$ of the S/F contact versus the ferromagnetic layer thickness $d_f$ at uniform magnetization.
According to the calculations, the most pronounced effect is observed at ferromagnet thicknesses ($d_f$) corresponding to the first minimum of $T_c(d_f)$. At such ferromagnet thicknesses, the nonuniform magnetization changes the interference conditions for the Usadel function component corresponding to the pairs penetrating into the ferromagnetic layer from the superconductor and the component reflected from the ferromagnet free boundary. Naturally, this leads to a rather complex dependence of the critical temperature on the skyrmion size. However, small distortions caused by the method of averaging the Usadel functions along the S/F interface at the skyrmion size close to $\xi_s$ cannot be excluded with confidence. The main qualitative result appears quite reasonable: the critical temperature in the skyrmion localization domain is higher than that for the other bilayer regions. The difference between the temperatures can be increased by special fitting of the superconductor and ferromagnet thicknesses under the conditions of high interface transparency. The chiral float [33] makes a qualitatively similar influence on superconductivity; however, it can exist only in sufficiently thick ferromagnetic films.

By varying the superconducting layer thickness, one can ensure a situation where superconductivity appears in the superconducting layer only near the skyrmion. Figure 3 shows a schematic representation of a peculiar island of superconductivity. This effect manifests itself at contact with magnetic vortices, the characteristic size of which is about the superconducting coherence length. It should be noted that some other parameters of the system may induce a bound state between the skyrmion and Abrikosov vortex; this situation was considered in [18, 34, 35]. We plan to consider the influence of the skyrmion on the critical temperature in this case in further studies, along with the case of strong external magnetic field, which is of great practical importance. It is also noteworthy that the proximity effect considered in this study is not the only mechanism of the interaction between the Abrikosov vortex and magnetic skyrmion. As shown, e.g., in [17–19], the electromagnetic interaction plays a very important role in these systems and is sufficient for the formation of this bound state. In the case of the superconducting island bound to a nanoscale vortex, the critical temperature is about 10–20% of the critical temperature of a solitary superconductor. Upon removal from the island, the density of Cooper pairs decreases exponentially on the scale $\xi_s$. Figure 4 shows the dependence of the critical temperature of the island on the skyrmion size.

The significant influence of nanoscale spin vortices on the critical temperature, in combination with topological protection and a low current density necessary for their motion [36–38], makes it possible to efficiently use these systems as superconducting spin valves [39–41]. For example, the superconducting island localized between superconducting edges may serve as a mobile bridge for the superconducting spin valve (see Fig. 5). The superconducting layer thickness and temperature are chosen such that the S/F system is close to the transition to the superconducting state. The occurrence of a skyrmion in this region will cause a transition of the bridge to the superconducting state.

To summarize, within the proximity effect theory in the dirty limit, an approximate approach has been proposed to calculate the critical temperature for the contact between a superconductor and an inhomogeneous magnet. The contact with a ferromagnet in the conical phase and the contact with a solitary skyrmion against the background of uniform magnetization have
be considered. As one would expect, the skyrmion affects the critical temperature most significantly in the case of fairly thin ferromagnet layers and a high transparency of the S/F interface. With specially chosen layer thicknesses, one can induce superconductivity only in the localization domain of the spin vortex. The resulting superconducting island bound to the magnetic skyrmion can potentially be used as a mobile bridge for the supercurrent.

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CONFLICT OF INTEREST
The authors declare that they have no conflicts of interest.

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