Quantum Oscillations and π-States in Multiply Connected Ferromagnet-Superconductor Hybrids

A. V. Samokhvalov, A. S. Mel'Nikov, Alexandre I. Buzdin

Quantum Oscillations and π-States in Multiply Connected Ferromagnet-Superconductor Hybrids

A.V. Samokhvalov · A.S. Mel'nikov · A.I. Buzdin

Abstract On the basis of Usadel equations, we consider superconductivity nucleation and Josephson current in multiply connected mesoscopic superconductor/ferromagnet (S/F) hybrids. We demonstrate that the exchange field can provoke an increase in the critical temperature T_c of the superconducting transition in the magnetic field. We study the Josephson effect in S/F composites and demonstrate that the negative sign of the critical current (π state) can be realized in such structures despite a dispersion of the distances between different segments of superconducting electrodes.

Keywords SF hybrids · Usadel equations · Little–Parks oscillations · π state

The particularity of the proximity effect in superconductor/ferromagnet (S/F) hybrid structures is the damped oscillatory behavior of the Cooper pair wave function inside the ferromagnet [1, 2] (for the reviews, see [3]). This special type of the proximity effect results in the π Josephson S/F/S junction [4], which has at the ground state the opposite sign of the superconducting order parameter in the electrodes. Both the damped oscillatory S/F proximity effect and the π states are proven to be very robust vs. different types of the impurities scattering (magnetic and nonmagnetic), interface transparency, and exist in the diffusive (dirty) limit.

A.V. Samokhvalov (✉) · A.S. Mel'nikov
Institute for Physics of Microstructures, Russian Academy of Sciences, 603950 Nizhny Novgorod, Russia
e-mail: samokh@ipm.sci-nnov ru

A.I. Buzdin
Institut Universitaire de France and University Bordeaux, LOMA UMR-CNRS 5798, 33405 Talence Cedex, France

Naturally, at the first stage, the S/F systems with planar (layered) geometry and well-controlled layers thickness have been considered [3]. However, it may be of interest to address a question how the unusual proximity effect and the π states could manifest itself in multiply connected geometry and/or in S/F structures with a poorly defined thickness of ferromagnetic (F) spacer between superconducting (S) electrodes. The goal of this paper is to study the hallmarks of the π-superconductivity in two model hybrid S/F systems (see Fig. 1). The first system consists of thin-walled hollow S cylinder placed in electrical contact with a F core. The second one is two S rod-shaped electrodes embedded in a ferromagnet.

Vortex States in Thin-Walled S Cylinder The Little–Parks effect [5] is known to be a sensitive experimental tool for observation of interference phenomena in multiply connected systems, and thus it is natural to use it for the study of the peculiarities of superconductivity nucleation in mesoscopic S/F hybrids. We consider a generic example of hybrid S/F systems with a cylindrical symmetry: F cylindrical filament (core) surrounded by a thin-walled S shell (Fig. 1a).

The calculations of the second-order superconducting phase transition temperature T_c were based on the linearized Usadel equations [6] for the averaged anomalous Green's functions F_f and F_s for the F and S regions, respectively (see [7, 8] for details). We look for a homogeneous along core solution characterized by certain angular momentum L. Figure 2 shows examples of dependences of the critical temperature T_c on the external magnetic field H for different values of the S/F interface resistance. The phase boundary exhibits Little–Parks oscillations, indicating transitions between the states with different angular momenta $L \to L \pm 1$ of the S order parameter. The interplay between the oscillations of T_c due to the orbital effect and the oscillations due to

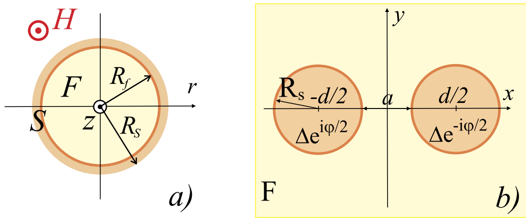

Fig. 1 The cross section of the hybrid S/F systems under consideration: (**a**) thin-walled S shell around a F cylinder; (**b**) two identical S cylindrical rod-shaped electrodes of radius R_s surrounded by a F metal

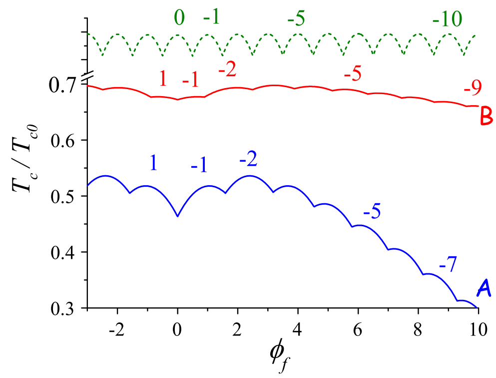

Fig. 2 The typical dependences of the critical temperature T_c on magnetic flux $\phi_f = \pi R_f^2 H/\Phi_0$ enclosed in F cylinder for different values of the S/F interface resistance $R_A < R_B$. The *numbers* near the *curves* denote the corresponding values of vorticity L. The *dashed line* shows the Little–Parks oscillations, when the exchange interaction is canceled

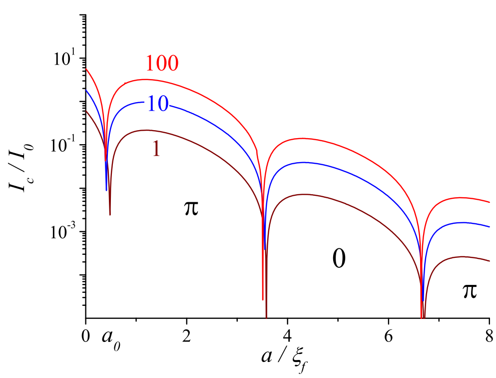

Fig. 3 Influence of the electrode radius R_s on the dependence of the critical current I_c on the distance a between two S rod-shaped electrodes embedded in F-metal. The *numbers* near the *curves* denote the values of the radius R_s in the units of ξ_f

the exchange field results in breaking of the strict periodicity of the $T_c(H)$ dependence. We have also observed a slow modulation of the amplitude of the quasiperiodic $T_c(H)$ oscillations and a shift of the main T_c maximum to finite external magnetic field values.

S/F/S Junction Between Two Superconducting Rod Now we proceed with calculation of the Josephson critical current between two rod-shaped S electrodes of a radius R_s surrounded by a F metal (Fig. 1b). The supercurrent $I_s(\varphi) = I_c \sin(\varphi)$ flowing across this S/F/S weak link depends on the phase difference φ between the order parameters of the rods: $\Delta_{1,2} = \Delta e^{\pm i\varphi/2}$. In the dirty limit and for large enough distance between the S cylinders ($a = d - 2R_s > 2\xi_f$), the strong exchange field ($h \gg \pi T_c$) and $R_s \gg \xi_f$ the expression for the critical current I_c reads (see [9] for details):

$$I_c(a, R_s)/I_0 = \frac{2dR_s}{\xi_f} \int_0^\infty dy \, \frac{e^{-2(\sqrt{y^2+d^2/4}-R_s)/\xi_f}}{y^2 + d^2/4} \times \cos\left(2\frac{\sqrt{y^2+d^2/4}-R_s}{\xi_f} + \frac{\pi}{4}\right), \qquad (1)$$

$$I_0 = \frac{\pi\sigma_n \Delta \xi_f^2}{2\sqrt{2}e\gamma_b^2\xi_n^2} \tanh\left(\frac{\Delta}{2T}\right).$$

Here, $\xi_f = \sqrt{D_f/h}$, $\xi_n = \sqrt{D_f/2\pi T_c}$, D_f, and σ_n are the diffusion constant and the normal state conductivity of the F-metal, and the parameter $\gamma_b = R_b\sigma_n/\xi_n$ related to the boundary resistance per unit area R_b. In Fig. 3 we present some typical plots of the critical current I_c vs. the distance a calculated from Eq. (1). The 0-π transitions are observed to be very robust with respect to a geometry of the S/F/S junction and are determined rather by the thickness of the F spacer between S electrodes then by a shape of the electrodes. For fixed thickness of the F spacer, these transitions can be triggered by temperature variation. Note that a set of superconducting particles embedded in a ferromagnetic matrix realizes an intrinsically frustrated Josephson network, which may reveal a spontaneous current.

Acknowledgements This work was supported, in part, by the Russian Foundation for Basic Research, by the Program "Quantum Physics of Condensed Matter" of RAS, by the Russian Agency of Education under the Federal Program "Scientific and Educational Personnel of Innovative Russia in 2009–2013," and by the European IRSES program SIMTECH (Contract No. 246937).

References

1. Buzdin, A.I., Bulaevskii, L.N., Panyukov, S.V.: Pis'ma Zh. Eksp. Teor. Fiz. **35**, 147 (1982)
2. Buzdin, A.I., Yu, K.M.: Pis'ma Zh. Eksp. Teor. Fiz. **53**, 308 (1991)
3. Buzdin, A.I.: Rev. Mod. Phys. **77**, 935 (2005)
4. Ryazanov, V.V., et al.: Phys. Rev. Lett. **86**, 2427 (2001)
5. Little, W.A., Parks, R.D.: Phys. Rev. Lett. **9**, 9 (1962)
6. Usadel, L.: Phys. Rev. Lett. **25**, 507 (1970)
7. Samokhvalov, A.V., Mel'nikov, A.S., Buzdin, A.I.: Phys. Rev. B **76**, 184519 (2007)
8. Samokhvalov, A.V., Mel'nikov, A.S., Ader, J.-P., Buzdin, A.I.: Phys. Rev. B **79**, 174502 (2009)
9. Samokhvalov, A.V., Buzdin, A.I.: SUST **24**, 024003 (2011)