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Unusual boundary effect on coherency in two-band superconductors

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ABSTRACT

We demonstrate that restoration of two-band superconductivity near the surface of the system is governed by length scales which are drastically different from correlation lengths. Similar to the one-band case, one of the characteristic lengths diverges at critical temperature T_c, while another one shows unusual behaviour having singularity at $T_{c+} < T_c$. By moving away from the boundary, these scales approach correlation lengths in the bulk state, where the divergence at T_{c+} is removed by arbitrary weak interband coupling. The peculiarity can be manifested in proximity sandwich where T_{c+} becomes an inflection point for critical temperature being a function of superconducting layer thickness.

1. Introduction

Recently discovered multiband superconductors – Fe-based compounds and MgB_2 – demonstrate properties beneficial for various applications [1–4]. An implementation of these materials requires superconducting samples of reduced dimensionality. The fabrication and characterization of such systems is nowadays actively investigated [5–7].

The reduction of the sample thickness considerably affects superconducting properties. The critical temperature usually shows gradual decrease from the bulk value as film becomes thinner [8]. This behaviour can be explained by the appearance of degraded non-superconducting layers on the surface giving rise to proximity effect. Striking example of proximity phenomenon is surface-induced superconductivity in ultrathin FeSe films grown on $SrTiO_3$ substrate [9].

Hybrid structures involving multiband superconductors demonstrate number of non-trivial properties. Proximity to a superconductor with a lower transition temperature is able to enhance multiband superconductivity [10]. Contrariwise, conventional superconductivity can be suppressed by contact with nominally stronger two-gap superconductor [11]. The interface of multiband superconductor can reverse interband phase [12] or even harbour the time-reversal-symmetry-breaking state [13,14].

The textbook knowledge on proximity effect in conventional superconductors tells that evolution of superconductivity near interface is governed by correlation length [15]. Recently, it was established that multicomponent superconductors contain multiple correlation lengths [16–18] which results in the multiscale physics manifesting, in particular, in the vortex core stretching [19] and unusual magnetic response [20]. The subject provoked discussion [21–23] which revealed strong discrepancy between correlation lengths driving bulk asymptotic behaviour of gap functions and healing lengths which define restoration of superconductivity near normal boundary. This peculiarity of multiband systems did not attract proper attention whereas it seems to be very important for proximity systems where physics near interface plays crucial role. Multiscale effect on proximity phenomenon was not systematically analysed as well.

In this contribution, we investigate coherency properties of two-band superconductor near its boundary, where system is affected by the interplay between proximity effect and multiscale physics (no time-reversal symmetry breakdown is involved). We calculate characteristic length scales for superconductivity correlations in the vicinity of the surface and find that they are drastically deviated from the bulk counterparts. The behaviour is in strong contrast to the one-band superconductivity model, where coherency is not affected by the boundary, meaning that same length scale drives superconductivity both near system surface and in the bulk. We demonstrate that surface-driven modifications of superconductivity correlations can result in non-trivial effects in normal/two-band superconductor binary systems. This peculiarity should be taken into account when tuning multiband superconductivity for practical applications.

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2. Formalism

Various approaches exist to describe mutual influence of the subsystems in contact. Microscopic models, such as McMillan tunneling model [24] and Green's functions approach [25] are powerful tools for analysis of proximity effects. Below we discuss phenomenological description based on the Ginzburg–Landau formalism supplemented by suitable boundary conditions at the interface [26].

We start with the Ginzburg–Landau equations for clean s-wave two-band ($\alpha = 1, 2$) superconductor in zero magnetic field. By taking into account Josephson tunneling between bands, the free-energy density $F = \sum_\alpha F_\alpha$ is given by

$$F_\alpha = a_\alpha|\delta_\alpha|^2 + b_\alpha|\delta_\alpha|^4/2 - c\delta_\alpha\delta^*_{3-\alpha} + K_\alpha|\nabla\delta_\alpha|^2, \tag{1}$$

where expansion coefficients read as [27]

$$a_\alpha = W_{3-\alpha,3-\alpha}/\det\hat{W} - \rho_\alpha \ln[0.13\hbar\omega_D/(k_B T)],$$
$$b_\alpha = 0.11\rho_\alpha/(k_B T)^2, \qquad K_\alpha = b_\alpha\hbar^2 v^2_{F\alpha}/6, \tag{2}$$

and $c = W_{12}/\det\hat{W}$. Here $W_{\alpha\alpha} > 0$ and $W_{12} = W_{21}$ are matrix elements for intraband and interband pair-transfer interactions, ρ_α is the density of states at the Fermi level, $v_{F\alpha}$ is the Fermi velocity in the relevant band, and $\hbar\omega_D$ is the Debye energy cut-off. Note that in this model $\det\hat{W} > 0$ is assumed.

Spatial variation of gap fields δ_α is governed by the Ginzburg–Landau equations

$$a_\alpha\delta_\alpha - c\delta_{3-\alpha} + b_\alpha|\delta_\alpha|^2\delta_\alpha = K_\alpha\nabla^2\delta_\alpha, \tag{3}$$

supplemented by relevant boundary condition. Following de Gennes [28], we require $\mathbf{n}\nabla\delta_\alpha = \sum_\beta \tau_{\alpha\beta}\delta_\alpha$ at the boundary of a superconductor, where $\mathbf{n}$ is unit vector normal to the surface and $\hat{\tau}$ is matrix of inverse extrapolation lengths whose coefficients satisfy $\tau_{\alpha\alpha} = \tau^*_{\alpha\alpha}$ and $\tau_{21} = \tau^*_{12}K_1/K_2$. To preserve time-reversal symmetry on the level of boundary condition, we take $\tau_{12} = \tau^*_{12}$.

Extrapolation lengths entering matrix $\hat{\tau}$ characterize the interaction between superconductor and ambient environment and, in particular, the penetration of order parameters into it. Generally, extrapolation length can vary in wide limits ranging from negative values (contact with nominally stronger superconductor) until infinity (neighbourship with vacuum or insulator). Extrapolation length depends also on fabrication parameters [29] and applied field [30].

For further analysis it is convenient to rescale quantities entering equation (3). By introducing bulk gaps $|\Delta_\alpha|$ and length $\lambda = \Phi/\sqrt{8\pi\sum_\alpha K_\alpha|\Delta_\alpha|^2}$, where $\Phi = \hbar c/(2e)$, we scale distances as $X = \lambda x$ and order parameters as $\delta_\alpha = |\Delta_\alpha| f_\alpha e^{i\psi_\alpha}$. By assuming that gap fields depend only on a distance x to the interface, equation (3) can be written in the form

$$\mathcal{A}_\alpha f_\alpha + G^2_\alpha f_\alpha \psi'^2 - \mathcal{C}_\alpha f_{3-\alpha}\cos\psi + \mathcal{B}_\alpha f^3_\alpha = f''_\alpha,$$
$$\mathcal{C}_1 f_1 f_2 \sin\psi = (G_1 f^2_1 \psi')', \qquad \psi'_2 = -G_2\psi', \tag{4}$$

where $\psi = \psi_1 - \psi_2$, $\mathcal{A}_\alpha = a_\alpha\lambda^2/K_\alpha$, $\mathcal{B}_\alpha = b_\alpha|\Delta_\alpha|^2\lambda^2/K_\alpha$, $\mathcal{C}_\alpha = c|\Delta_{3-\alpha}|\lambda^2/(K_\alpha|\Delta_\alpha|)$ and $G_\alpha = \mathcal{C}_\alpha f^2_{3-\alpha}/(\sum_\beta \mathcal{C}_\beta f^2_{3-\beta})$. Spatial dependence of the phases generates supercurrent in the bands, however, net supercurrent is vanishing. Bulk gaps $|\Delta_\alpha|$ are defined by Eq. (4) in homogeneous limit, where $f_\alpha = 1$ and $\psi = 0$ provided that $W_{12} > 0$.

2.1. Asymptotic near bulk state

Deviations $\epsilon_\alpha = 1 - f_\alpha$ from the bulk state determined by $f_\alpha = 1$ and $\psi = 0$ are characterized in the linear approximation by $(\mathcal{A}_\alpha + 3\mathcal{B}_\alpha)\epsilon_\alpha - \mathcal{C}_\alpha\epsilon_{3-\alpha} = \epsilon''_\alpha$. We introduce mixing angles $\varphi_\pm$ and new fields $\epsilon_\pm$ as follows

$$\epsilon_1 = \cos\varphi_-\epsilon_- - \sin\varphi_+\epsilon_+, \tag{5}$$
$$\epsilon_2 = \sin\varphi_-\epsilon_- + \cos\varphi_+\epsilon_+.$$

Choice $\mathcal{C}_1\tan\varphi_- = \mathcal{C}_2\tan\varphi_+ = 2(\xi^2_- - \xi^2_1)/(\xi^2_1\xi^2_-)$, where $2\xi^{-2}_\alpha = \mathcal{A}_\alpha + 3\mathcal{B}_\alpha$, decouples equations as $\epsilon''_\pm = 2\epsilon_\pm/\xi^2_\pm$. The letter defines correlation lengths $\xi_\pm$ for a two-band system

$$2\xi^{-2}_\pm = \xi^{-2}_1 + \xi^{-2}_2 \pm \sqrt{(\xi^{-2}_1 - \xi^{-2}_2)^2 + \mathcal{C}_1\mathcal{C}_2}. \tag{6}$$

Note that correlation lengths $\xi_\pm$ are dimensionless and given in the units of λ.

In the absence of interband coupling, coherency in each condensate is characterized by length scale $\xi_{1,2}$, respectively. Interband pairing mixes coherency channels so that superconductivity restoration in the joint condensate consists of two modes scaled by $\xi_\pm$. At that, mixing modifies temperature dependencies for dimensional correlation lengths $\xi_\pm\lambda$ dramatically: $\xi_-\lambda$ behaves critically diverging at the phase-transition point T_c, while $\xi_+\lambda$ stays always finite [31,32].

In addition, bulk state is characterized by separate length due to interband phase variation $(\mathcal{C}_1 + \mathcal{C}_2)\psi = \psi''$. Here $\mathcal{C}_1 + \mathcal{C}_2$ is dimensionless mass of the Leggett mode.

2.2. Asymptotic near boundary

In the vicinity of the boundary, interband phase can have nontrivial value signaling time-reversal symmetry breaking [33]. In this case density and phase modes become mixed. Next we assume that interface suppresses superconductivity as for the border with magnetic material or normal metal, and neglect time-reversal symmetry breakdown taking $\psi \mod \pi = 0$. Then the Ginzburg–Landau equations can be linearised as $\mathcal{A}_\alpha f_\alpha \mp \mathcal{C}_\alpha f_{3-\alpha} = f''_\alpha$, where upper sign corresponds to $\psi = 0$. We decouple bands using mixed modes

$$f_1 = \cos\theta_- f_- - \sin\theta_+ f_+ \tag{7}$$
$$f_2 = \sin\theta_- f_- + \cos\theta_+ f_+.$$

By taking $\mathcal{C}_1\tan\theta_- = \mathcal{C}_2\tan\theta_+ = \pm 2(\Gamma_- - \Gamma_1)/(\Gamma_-\Gamma_1)$, where $\Gamma_\alpha = 2/\mathcal{A}_\alpha$, we obtain $f''_\pm = 2f_\pm/\Gamma_\pm$ with

$$2/\Gamma_\pm = 1/\Gamma_1 + 1/\Gamma_2 \pm \sqrt{(1/\Gamma_1 - 1/\Gamma_2)^2 + \mathcal{C}_1\mathcal{C}_2}. \tag{8}$$

Dimensionless length scales of the problem are given by $\gamma_\pm = \sqrt{|\Gamma_\pm|}$. The latter ones define the healing of two-band superconductivity close to its interface.

Dimensional lengths $\gamma_\pm\lambda$ have very unusual properties [34] diverging respectively at the temperatures $T_{c\pm}$ given by

$$2/\ln[1.13\hbar\omega_D/(k_B T_{c\pm})] = \sigma \mp \sqrt{\sigma^2 - 4\rho_1\rho_2\det\hat{W}}, \tag{9}$$

where $\sigma = \sum_\alpha \rho_\alpha W_{\alpha\alpha}$. The larger temperature $T_{c-} \equiv T_c$ corresponds to the critical temperature of the joint condensate and it is a point where $\gamma_-\lambda$ becomes infinitely large. Smaller temperature T_{c+} defines singularity of $\gamma_+\lambda$. This point has physical meaning only for vanishing interband interaction when $T_{c\mp}$ approach critical temperatures for non-interacting condensates, $T_{c1,2}$, respectively.

While bulk state of two-band superconductor is characterized by one divergent and one finite correlation length, coherency near time-reversal-symmetry respecting surface is defined by two divergent length scales. Such a peculiarity is in strong contract to conventional model, where same length scale appears in both spatial domains.