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Tunneling conductance through the half-metal/conical magnet/superconductor junctions in the adiabatic and non-adiabatic regimes: Self-consistent calculations

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H I G H L I G H T S

- The adiabaticity of the electron transport through the HM/CM/SC heterojunction is studied.
- The proximity effect is included in the self-consistent calculations.
- The adiabaticity is changed by the period of the exchange filed modulation.
- The tunneling conductance exhibits different properties in adiabatic and non-adiabatic regimes.

A R T I C L E I N F O

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The tunneling conductance through the half-metal/conical magnet/superconductor (HM/CM/SC) junctions is investigated with the use of the Bogoliubov–de Gennes equations in the framework of Blonder–Tinkham–Klapwijk formalism. Due to the spin band separation in the HM, the conductance in the subgap region is mainly determined by the anomalous Andreev reflection, the probability of which strongly depends on the spin transmission in the CM layer. We show that the spins of electrons injected from the HM can be transmitted through the CM to the SC either adiabatically or non-adiabatically depending on the period of the spatial modulation of the exchange field. We find that the conductance in the subgap region oscillates as a function of the CM layer thickness wherein the oscillations transform from the irregular pattern in the non-adiabatic regime to the regular one in the adiabatic regime. For both adiabatic and non-adiabatic transport regimes the conductance is studied over a broad range of parameters determining the spiral magnetization in the CM. We find that in the non-adiabatic regime, the decrease of the exchange field amplitude in the CM leads to the emergence of the conductance peak for the particular CM thickness in agreement with recent experiments.

1. Introduction

Recently the quantum transport through the ferromagnet/superconductor (FM/SC) junctions has attracted the growing interest due to a possible existence of the spin-triplet pairing [1–4] and novel transport phenomena related to this unique superconducting state [5–7]. For the s-wave superconductors with the spatially symmetric orbital part of the Cooper pair wave function, its spin part is antisymmetric, which means that the spin-singlet seems to be the only possible state for the Cooper pair. However, many years ago Berezinskii [8] proposed a possible existence of the spin-triplet state in a system with the s-wave interaction. The triplet pairing correlations proposed by Berezinskii are odd in time (or frequency) and can appear in the systems with some time-reversal symmetry breaking mechanism. Recent studies suggest that the spin-triplet Cooper pair correlations can be induced and observed experimentally in the FM/SC junctions with the spin-active or magnetically inhomogeneous interface [9–11].

In the normal metal/superconductor (NM/SC) junctions the electrons incident onto the interface from the NM side are reflected as holes with opposite spins. This mechanism, known as the normal Andreev reflection [12], leads to the proximity effect, i.e. the superconducting pairing correlations penetrate into the normal metal over the distance as long as one micron at low temperatures [13]. The proximity effect significantly changes if we replace the normal metal by the ferromagnet. The exchange

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interaction in the ferromagnet leads to the different Fermi wave vectors for electrons with opposite spins forming the Cooper pairs. This wave vector mismatch is compensated by the non-zero total momentum of the Cooper pairs giving rise to the oscillations of the spin-singlet superconducting pair correlations in the ferromagnet [5,14], known as the Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) oscillations [15,16]. Since the exchange field tends to align the electron spins along the field direction, the spin-singlet superconducting correlations in the ferromagnet are strongly suppressed leading to the short-range penetration length. In contrast to the short-range proximity effect for the spin-singlet state, the spin-triplet state $m=\pm 1$, with both spins directed along the exchange field, is robust against the pair breaking mechanism induced by the exchange interaction. Therefore, the spin-triplet superconducting correlations for $m=\pm 1$, if they exist, can penetrate into the ferromagnet over the distance comparable to this observed in the NM/SC junctions. This phenomenon, called long-range proximity effect was predicted theoretically by Bergeret et al. (see Refs. [6,9,10]) in the FM/SC junctions with the spin-active or magnetically inhomogeneous interface. Despite a few theoretical ideas to induce the spin-triplet pairing, including the effect of domain wall [17], spin–orbit coupling [18], spin-dependent potential [19], or spin-active interface [20] so far, the direct evidence of the spin-triplet supercurrent has been observed only in the multilayer FM/FM/SC systems with a non-collinear magnetization of the ferromagnetic layers [21–23].

The first experimental hint for the long-range proximity effect was reported in a half-metal Josephson junction based on CrO_2 [24]. However, since the measured critical current varied by two orders of magnitude in similar samples, the results of this experiment [24] needed to be confirmed. The strong evidence for the long range proximity effect was then reported in the Josephson junctions based on Co [25]. The dependence of the critical current on the Co layer thickness, which agrees with the theoretical expectations, provides a strong experimental confirmation of the appearance of the spin-triplet pairing in the FM/SC heterojunctions. Further studies of the spin-triplet pairing concerned the FM/SC/FM and FM/FM/SC junctions with a relative magnetization between the ferromagnets. The spin triplet pairing in the FM/SC/FM nanostructures with an arbitrary angle between the magnetization of the FM layers was theoretically studied by Haltermann et al. in Refs. [26–29]. The authors of Refs. [26–29] obtained the self-consistent solutions of the microscopic Bogoliubov–de Gennes (BdG) equations and analyzed the spin-triplet correlations as a function of the relative magnetization between the magnetic layers. The self-consistent calculations [26–29] allowed to confirm the experimentally observed angular dependence of the critical temperature T_c, which monotonically increases due to the presence of the long range spin-triplet correlations. T_c reaches minimum if the relative magnetization of the layers is parallel and maximum for the antiparallel magnetization [29]. A different behavior was observed for the FM/FM/SC nanostructures for which the critical temperature is minimal in the case of perpendicular alignment of the magnetization [30,31].

The research of the spin-triplet pairing in the FM/FM/SC junctions has been recently extended to systems with the conical (helical) ferromagnets (CM). The long-range triplet supercurrent has been demonstrated for the Josephson junctions based on holmium (Ho)–cobalt (Co)–holmium (Ho) multilayer setup [32]. A nonmonotonic dependence of the critical supercurrent has been observed as a function of the Ho layer thickness, d_{CM}, with peaks for $d_{CM}=4.5$ nm and 10 nm. When increasing the Co layer thickness a slow decay of the critical current has been found in agreement with theoretical calculations [33]. Nevertheless, the theoretical model presented in Ref. [33] does not explain the complex dependence of the critical supercurrent on the Ho thickness. The nonmonotonic behavior of $I_C(d_{CM})$ has been obtained by Halász et al. in Ref. [34] who have performed calculations in the clean limit using Eliashberg equations. Similar dependence has been also demonstrated by the use of the Blonder–Tinkham–Klapwijk (BTK) approach in Refs. [35,36].

In the mentioned theoretical works [34–36] the proximity effect at the CM/SC interface has been neglected which means that the superconducting pair potential has been assumed to be a step function. However, as shown by the recent studies [37], only the self-consistent calculations of the tunneling conductance guarantee that the charge conservation law is satisfied. This means that one cannot properly determine the conductance in the FM/CM/SC heterostructures by using the non-self-consistent approach. Instead, the full self-consistent approach is needed. Although the self-consistent calculations of the spin-triplet correlations in two layered CM/SC junctions have been presented in Refs. [38,39], these studies do not include the analysis of the tunneling conductance, the influence of the FM layer attached to the CM and the influence of the magnetic structure in the CM layer which, as we will show in this paper, has a significant impact on the spin transmission and consequently the conductance in FM/CM/SC junctions. Therefore, the theoretical analysis of the tunneling conductance through the FM/CM/SC heterojunctions with the inclusion of the proximity effect in the full self-consistent framework has not been presented until now.

In the present paper we present the results of the full self-consistent calculations of the tunneling conductance through the HM/CM/SC junctions. The charge transport in the considered system is mainly determined by the anomalous Andreev reflection [40–43], the probability of which strongly depends on the spin transmission in the CM layer. We consider the conductance in two the cases for which the spin transport is adiabatic and non-adiabatic. The conductance is studied over a broad range of parameters determining the spiral magnetization in the CM. We show that the tunneling conductance in the HM/CM/SC junctions strongly depends on the spin transport regime.

The paper is organized as follows: in Section 2 we introduce the basic concepts of the theoretical scheme based on the self-consistent solution of the BdG equations and the BTK formalism. In Section 3 we present the results and discussion while Section 4 contains the summary.

2. Methods

We consider the FM/CM/SC structure schematically illustrated in Fig. 1 – note that, for general, we do not restrict our model to the junction based on the half-metal. The system is assumed to be infinite in the x–z plane while the y-axis is perpendicular to the layers with lengths denoted by d_{FM}, d_{CM}, d_{SC}, respectively.

The value and the direction of the exchange field $\mathbf{h}$ (the red arrow in Fig. 1), depends on the position. The exchange field is directed along the z-axis in the ferromagnet, $\mathbf{h}=(0,0,h_{FM})$, while, in the conical ferromagnet, $\mathbf{h}$ is given by

$$\mathbf{h}(y)=\begin{cases} h_{CM}\sin\alpha\sin\left(\beta_0+\dfrac{\beta y}{a}\right) \\ h_{CM}\cos\alpha \\ h_{CM}\sin\alpha\cos\left(\beta_0+\dfrac{\beta y}{a}\right) \end{cases}, \tag{1}$$

where h_{CM} is the exchange field amplitude, β_0 is the angle between the relative magnetization of the CM layer and the FM layer at the FM/CM interface, while α and β are the cone and rotation angle whose physical meaning is presented in Fig. 1(b). According to Eq. (1) the spatial period of the helical exchange field is $\lambda=2\pi a/\beta$,