arXiv:1604.03361v1 [cond-mat.supr-con] 12 Apr 2016

Influence of the FFLO-like State on the Upper Critical Field of a S/F Bilayer: Angular and Temperature Dependence

D. Lenk,[1] M. Hemmida,[1,2] R. Morari,[1,3,4] V. I. Zdravkov,[1,3,5] A. Ullrich,[1] C. Müller,[1] A. S. Sidorenko,[3] S. Horn,[1] L. R. Tagirov,[1,4] A. Loidl,[2] H.-A. Krug von Nidda,[2] and R. Tidecks[1]

[1] *Experimentalphysik II, Institut für Physik, Universität Augsburg, Universitätsstraße 1, D-86159 Augsburg, Germany*

[2] *Experimentalphysik V, Center for Electronic Correlations and Magnetism, Institut für Physik, Universität Augsburg, Universitätsstraße 1, D-86159 Augsburg, Germany*

[3] *D. Ghitsu Institute of Electronic Engineering and Nanotechnologies ASM, Academiei Str. 3/3, MD2028 Kishinev, Moldova*

[4] *Solid State Physics Department, Kazan Federal University, Kremlevskaya Str. 18, 420008 Kazan, Russian Federation*

[5] *Present Address: Institute of Applied Physics and Interdisciplinary Nanoscience Center, Universität Hamburg, Jungiusstraße 9A, D-20355 Hamburg, Germany*

(Dated: October 16, 2018)

We investigated the upper critical magnetic field, H_c, of a superconductor-ferromagnet (S/F) bilayer of $Nb/Cu_{41}Ni_{59}$ and a Nb film (as reference). We obtained the dependence of $H_{c\perp}$ and $H_{c\|}$ (perpendicular and parallel to the film plane, respectively) on the temperature, T, by measurements of the resistive transitions and the dependence on the inclination angle, θ, of the applied field to the film plane, by non-resonant microwave absorption. Over a wide range, $H_{c\perp}$ and $H_{c\|}$ show the temperature dependence predicted by the Ginzburg-Landau theory. At low temperatures and close to the critical temperature deviations are observed. While $H_c(\theta)$ of the Nb film follows the Tinkham prediction for thin superconducting films, the $Nb/Cu_{41}Ni_{59}$-bilayer data exhibit deviations when θ approaches zero. We attribute this finding to the additional anisotropy induced by the quasi-one-dimensional Fulde-Ferrell-Larkin-Ovchinnikov (FFLO)-like state and propose a new vortex structure in S/F bilayers, adopting the segmentation approach from high-temperature superconductors.

I. INTRODUCTION

Singlet superconductivity and ferromagnetism are two antagonistic orders. The formation of singlet Cooper pairs requires electrons with anti-parallel spins, whereas the ferromagnetism tends to align electron spins parallel. Nevertheless, Fulde-Ferrell[1] and Larkin-Ovchinnikov[2] (FFLO) predicted superconductivity on a ferromagnetic background, however, in a very narrow range of parameters (see Fig. 22 of Fulde's review[3]). Therefore, only a few experimental realizations exist so far, in heavy fermion and organic superconductors (see the work of Zwicknagl and Wosnitza[4] for a review).

For the heavy fermion system, $CeCoIn_5$, specific heat data[5,6], thermal conductivity[7], and penetration depth measurements[8] show evidence for the existence of the FFLO state. In quasi-two-dimensional organic superconductors evidence has been obtained from specific heat data[9] and magnetic torque studies[10,11]. However, a spatial oscillation of the order parameter, which is the main feature of the FFLO state, has not yet been observed directly.

In layered organic superconductors, an unusual dependence of the transition temperature on the field direction has been predicted theoretically[12–16]. It is based on the interplay between the vector potential of a magnetic field (applied parallel to the layered structure), the interlayer coupling, and the nodal structure of the order parameter (and its spatial modulation). These calculations shed new light on the interpretation of the results of experimental investigations[17,18] as fingerprints of the FFLO state.

In superconductor-ferromagnet (S/F) proximity effect systems, *e.g.* in S/F bilayers, a quasi-one-dimensional FFLO-like state can be realized by Cooper pairs migrating from the superconductor into the ferromagnet[19,20]. Due to the exchange splitting in the ferromagnet, the Cooper pair gains a non-zero momentum, resulting in an oscillating pairing wave function[19–23]. Its reflection at the outer surface of the F-layer leads to interference effects, yielding a superconducting transition temperature, T_c, oscillating as a function of the F-layer thickness, d_F[21,24,25].

In the presence of two F-layers (*i.e.* for F/S/F and S/F/F structures), the superconducting transition temperature depends on the relative orientation of their magnetizations[26,27]. Such systems represent superconducting spin valves, which can be switched between two states with different transition temperatures by magnetic fields, as demonstrated experimentally for the F/S/F[28–30] and S/F/F[31–33] case.

For non-collinear orientations of the magnetizations, an unconventional odd-in-frequency triplet s-wave pairing[23] is predicted, reducing the superconducting transition temperature[34]. Thus, a triplet spin-valve effect[34] can be established, which could be observed experimentally in S/F/F heterostructures[35,36] and seems to play a crucial role in a recently realized F/S/F memory element[37]. Moreover, in S/F/S Josephson junctions it is possible to realize π-junctions, in which the phase of the FFLO-like