Advanced Research Workshop

MESO-2012

Non-equilibruim and coherent phenomena at nanoscale

June 17-23, 2012

Chernogolovka, Russia

Organizers:
Landau Institute for Theoretical Physics and
Institute of Solid State Physics (Russian Academy of Sciences)

Manifestations of the long-range triplet pairing in superconductor-ferromagnet proximity heterostructures - theory versus experiment

L.R. Tagirov[1,2], V. I. Zdravkov[2,3], J. Kehrle[2], G. Obermeier[2], D. Lenk[2], H.-A. Krug von Nidda[2], C. Müller[2], S. Horn[2], R. Tidecks[2], M. Yu. Kupriyanov[4] and A. S. Sidorenko[3]

[1]*Kazan Federal University, 420008 Kazan, Russia*
[2]*Institut für Physik, Universität Augsburg, D-86159 Augsburg, Germany*
[3]*Institute of Electronic Engineering and Nanotechnologies ASM, Kishinev MD-2028, Moldova*
[4]*Skobeltsyn Institute of Nuclear Physics, Moscow State University, 119992 Moscow, Russia*

For superconductor-ferromagnet (S-F) proximity heterostructures with two or more F layers, the generation of a long-range, odd-in-frequency triplet pairing at non-collinear alignment of the F-layers magnetizations was predicted [1]. Here, we report on the first experimental observation of the triplet pairing manifestation in a $Nb/Cu_{41}Ni_{59}/Nb/Co/CoO_x$ spin-valve type proximity heterostructure [2]. The first, $\sim$ 12.8 nm thick, Nb layer is a conventional s-wave superconductor, while the second, very thin ($\sim$ 6 nm thick) Nb layer, sandwiched by ferromagnetic layers, acts as a normal conducting spacer. The key point of the sample design is that the CuNi-alloy layer has intrinsic equilibrium orientation of the magnetic moment perpendicular to the film plane. At the same time, the second ferromagnetic Co layer has intrinsic, in-plane orientation of the magnetic moment. So, the non-collinear mutual alignment of the F layers magnetic moments can be easily realized. The cobalt-oxide top layer provides exchange bias to the adjacent metallic Co layer allowing to acheve antiparallel alignment of the $Cu_{41}Ni_{59}$ and Co layers magnetic moments. Measuring the resistance of the samples as a function of an in-plane external magnetic field, we observed a sequence of transitions through normal conducting and superconducting phases, when the system goes along the magnetic hysteresis loop, from a parallel through a non-collinear to an anti-parallel and, finally, opposite directed parallel alignment of the magnetizations. The superconducting transition temperature, measured as a function of the in-plane magnetic field, has clearly visible downward cusp associated with the non-collinear alignment of the $Cu_{41}Ni_{59}$ and Co layers magnetic moments. The experimental findings described are consistent with the theoretical picture of the singlet superconductivity suppression by the long-range triplet pairing generation, predicted in Ref. [3].

[1] F. S. Bergeret, A. F. Volkov, and K. B. Efetov, Rev. Mod. Phys. 77, 1321 (2005).
[2] V.I. Zdravkov, et al. (submitted to PRL).
[3] Ya. V. Fominov, et al., Pisma v ZhETF 91 , 329 (2010) [JETP Lett. 91, 308 (2010)].

Double proximity effect in hybrid planar Superconductor-(Normal metal/Ferromagnet)-Superconductor structures

V. V. Ryazanov,[1] T. E. Golikova,[1] I. E. Batov,[1] F. Hübler,[2] D. Beckmann,[2]
T. Yu. Karminskaya,[3] M. Yu. Kupriyanov,[3] and A. A. Golubov[4]

[1]*Institute of Solid State Physics, Russian Academy of Sciences, 142432 Chernogolovka, Russia*
[2]*Karlsruhe Institute of Technology, 76021 Karlsruhe, Germany*
[3]*Lomonosov Moscow State University, Skobeltsyn Institute of Nuclear Physics, Moscow 119991, Russia*
[4]*Faculty of Science and Technology, University of Twente, 7500 AE Enschede, The Netherlands*

The coherent transport in Josephson superconductor - normal metal - superconductor (S-N-S) and superconductor - ferromagnet - superconductor (S-F-S) nanocontacts attracts intense interest nowadays. Ferromagnetic materials suitable for Josephson S-F-S junction fabrication have the superconducting order parameter decay length of about several nanometers [1] which is much smaller compared to the decay length in normal metal. To increase the decay length in structures with ferromagnets different types of Josephson junctions with complex bilayered (NF) and tri-layered (FNF) weak links have been proposed in theoretical work [2]. We report the fabrication of planar Josephson S-N-S and S-NF-S junctions and their characterization down to $T = 300$ mK. Samples were fabricated by electron beam lithography, using two-layer resist, and subsequent shadow deposition at two angles. We used aluminum films with thickness of 100 nm like superconducting banks, while a 15-60 nm thick copper film was used as a normal metal layer and 10 nm thick iron film as a ferromagnetic one in a planar bilayered barrier. Two different types of structures (S-N-S and S-NF-S) with the same geometry were investigated. It was found that current-voltage characteristics become hysteretic as temperature decreases despite the high transparency of SN-interfaces [2]. In the resistive part of current-voltage characteristics, the features related to the multiple Andreev reflections and the presence of a minigap were detected [3]. The nanofabricated S-NF-S structures of the second type had the space L between superconducting banks in the range of 30-200 nm. The Josephson supercurrent was observed in structures investigated. The critical current I_c of S-NF-S junctions was much smaller than that for S-N-S junctions. The rapid decrease of I_c with L increasing is due to the suppression of the superconducting proximity effect by the F-layer. In the differential resistance (density of state) characteristics of S-NF-S junctions a double peak peculiarity was observed at the voltage corresponding to the minigap. The effect observed can be explained by the induced electron spin polarization in the normal layer due to the ferromagnet.

[1] V. A. Oboznov, V.V. Bol'ginov, A. K. Feofanov, V. V. Ryazanov and A.I. Buzdin, Phys. Rev. Lett. **96**, 197003 (2006).
[2] T. Yu. Karminskaya, A. A. Golubov, M. Yu. Kupriyanov, and A. S. Sidorenko, Phys. Rev. B **81**, 214518 (2010).
[3] H. Courtois, M. Meschke, J. T. Peltonen, and J.P. Pekola, Phys. Rev. Lett. **101**, 067002 (2008).
[4] C. Cuevas, J. Hammer, J. Copu, J. K. Viljas, and M. Eschrig, Phys. Rev. B **73**, 184505 (2006).

Subgap states in disordered superconductors

M. A. Skvortsov and M. V. Feigel'man
L. D. Landau Institute for Theoretical Physics, 142432 Chernogolovka, Russia

We revise the problem of the density of states in disordered superconductors. Randomness of local sample characteristics translates to the quenched spatial inhomogeneity of the spectral gap, smearing the BCS coherence peak. We show that various microscopic models of potential and magnetic disorder can be generally reduced to the Abrikosov-Gor'kov model of paramagnetic impurities with some long-range fluctuating field. The resulting form of the density of states is generally described by two parameters: the width Γ measuring the broadening of the BCS peak, and the energy scale Γ_{tail} which controls the exponential decay of the density of the subgap states. We refine the existing instanton approaches [1, 2] for determination of Γ_{tail} and show that they appear as limiting cases of a unified theory of optimal fluctuations in a nonlinear system. Applications to experimentally relevant types of disorder including universal mesoscopic disorder [3] are discussed.

[1] A. I. Larkin and Yu. N. Ovchinnikov, Zh. Eksp. Teor. Fiz. **61**, 2147 (1971) [Sov. Phys. JETP **34**, 1144 (1972)].
[2] J. S. Meyer and B. D. Simons, Phys. Rev. B **64**, 134516 (2001); A. Lamacraft and B. D. Simons, Phys. Rev. Lett. **85**, 4783 (2000); Phys. Rev. B **64**, 014514 (2001).
[3] M. V. Feigel'man, M. A. Skvortsov, "Universal smearing of the BCS coherence peak in disordered superconductive films", arXiv:1112.2874.

Poster session

Spin entanglement and nonlocality of multifermion systems

Marsel R. Arifullin and Vitaly L. Berdinskiy
Orenburg University, Pobedy av., 13, Orenburg, Russia

The fundamental property of electron spin S = 1/2 is very perspective for usage as the information carrier in spintronics, quantum computing and quantum cryptography. However, to be used any electron spin should be extracted from the ensemble of undistinguished particles, and spin properties of such ensemble should be known. Spin states of odd number N of undistinguished fermions and their properties have been studied in details. Spin states are proved to be determined by the Pauli's principle unequivocally and should be described by spin density matrices (SDM). The initial step for calculation of SDM is the antisymmetric fermion wavefunction chosen as the Slater determinant. The effective algorithm for calculation of multispin SDM has been developed. Such SDM are shown can be presented as the normalized sum of nonorthogonal projector operators onto all possible multifermion singlet states

$$\rho_N = 2^{N/2}(N/2)!(N!)^{-1}\sum_P P(\mid S_{ij}S_{kl}S_{mn}\ldots ><S_{ij}S_{kl}S_{mn}\ldots \mid), \tag{1}$$

here P means all possible permutations of the indexes i,j,k,l,m,n..., and S are the singlet spin state of the fermion pair. The Sylvester criterion of nonnegativity together with the Peres-Horodecki one were used to prove that the SDM (1) describes entangled spin states of any multifermion subsystems. The important case is the twospin subsystem. Taking the trace over spin states of all the extra fermions the SDM

$$\rho_2 = 4^{-1}(N+2)(N-1)^{-1}\mid S><S\mid +4^{-1}(N-2)(N-1)^{-1}(\mid T_+><T_+\mid + \mid T_0><T_0\mid + \mid T_-><T_-\mid) \tag{2}$$

Usage of the Peres-Horodecki criterion proves that the twospin subsystem is not entangled in spite of the fact that spin state of any separate fermion is entangled with the rest of the multifermion system. This result illustrates the violation of transitivity of spin entanglements: the entanglement of system A and C does not follows from the fact that the system A is entangled with the system B, and the system B is entangled with the system C. Violation of the Bell's inequalities was proved for the case if the initial fermion system decays and produces one fermion.

Josephson φ-device concept based on complex nanostructures with normal metal/ferromagnet bilayer

S. V. Bakurskiy,[1] N. V. Klenov,[1] A. A. Golubov,[2] and M. Yu. Kupriyanov[3]
[1]*Faculty of Physics, Moscow State University, 119992, Leninskie Gory, Moscow, Russia*
[2]*Faculty of Science and Technology, University of Twente, 7500 AE Enschede, The Netherlands*
[3]*Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, 119992, Russia*

The φ-junction is the Josephson device with nontrivial ground state phase ($0 < \varphi < \pi$) created by non-sinusoidal ($I_S(\varphi) = A\sin(\varphi) + B\sin(2\varphi) + \ldots$) current phase relation (CPR) with a relatively large and negative amplitude of the second harmonic B. This junction has applicability in superconductive quantum circuits, e.g. qubits or quantum detectors. The competition of its creation associated with the fact, that required CPR can't be fulfilled on the base of single-layer devices. The previously proposed concepts use the arrays of 0- and π- ferromagnet SFS junctions [1, 2] featured by the large scale.

In this work we have demonstrated that the structures composed from longitudinally oriented normal and ferromagnet films in the weak link region can be used as reliable φ-device. In this case F-layer opens a window of the relative smallness of the first harmonics amplitude A and N-layer provides the negative sign of the second one. To prove it, in the frame of Usadel equations we solved two dimensional boundary problem for different geometries of S-NF-S structures and found analytical criteria of φ-state existence. Finally we numerically estimated those concepts and showed the structure with scale in order of 100 nm and critical current equal to 3 μA in the φ-state.

The support by RFBR grant 11-02-12065-ofi_m is gratefully acknowledged.

[1] R.G. Mints, Phys. Rev. B 57, R3221 (1998).
[2] N. G. Pugach, E. Goldobin, R. Kleiner, D. Koelle, Phys. Rev. B 81, 104513 (2010).