Superconducting and Magnetic Hybrid Structures

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Book of Abstracts

Bogoliubov Laboratory of Theoretical Physics

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Contents

Peculiarities of the magnetic moment dynamics in hybrid superconducting Josephson junctions

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The anomalous Josephson structures with coupled superconducting and magnetic characteristics allows the manipulation of magnetic properties by Josephson current [1]. In junctions with a strong spin-orbit coupling (φ_0 Josephson junction), we demonstrate the appearance of negative differential resistance on the IV characteristic, resulting in an additional locking step of magnetic precession [2]. We show that it is possible to control not only the frequency but also the amplitude of the magnetic precession in the locking region. In addition to this, for junction with electromagnetic coupling as in nanomagnet coupled to Josephson junctions [3,4], an irregular easy axis reorientation occurs due to several precessional motions that are related to chaotic behavior and orbits with different periodicity in the ferromagnetic resonance region [5]. This opens unique perspectives for the control and manipulation of magnetic moment in hybrid superconducting systems and spintronics devices.

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Ability to control magnetization precession in a shunted φ_0 junction

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Manipulation of the magnetic properties of the φ_0 junction is attracting much attention today. We demonstrate the possibility of controlling the magnetic precession by superconducting current in the region of ferromagnetic resonance in a shunted φ_0 junction. In particular, an increase in the intensity of magnetic precession is observed in the region of parallel resonance . This effect is increasing with increasing parameters of the φ_0 transition, such as the spin-orbit interaction, the ratio of the Josephson energy to the magnetic energy, and the magnitude of the Gilbert damping.

Single-photon detectors based on Josephson junctions

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Photon counters are required in many applications, like astrophysics experiments, quantum optics, atomic physics, and quantum information processing. One of the major challenges in this area is to produce devices capable to detect single photons of longer and longer wavelengths, which are required, for example, in the detailed study of the Cosmic Microwave Background (CMB) radiation and in the detection of dark matter particles. Extending the range of wavelengths for detectable photons into the microwaves spectrum is currently under investigation. Eventually the most promising technologies that may be employed to achieve this objective are based on superconducting devices. There are two main types of such detectors: the cold electron bolometer and the Josephson junction (JJ) detector.

We present a quantum mechanical description of the JJ detector for two types of configurations, taking into consideration also the antenna [1, 2, 3]. The model is based on the macroscopic quantum tunneling formalism (MQT). We derive the Hamiltonian operators for each configuration and write the Schrödinger equations. In both cases, the system is equivalent to a quantum particle moving in a two-dimensional potential landscape with an infinite number of local minima. Initially, the system is prepared with the particle in a metastable state in one of these minima, and the detection of the photon is represented as the excitation of this particle over the potential barrier, out of the initial local minimum [1].

Estimations based on this model show that for typical values of the JJ and antenna parameters, such devices may detect photons at least up to 1 cm wavelengths.

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Attraction and repulsion between a Néel-type magnetic skyrmion and a Pearl superconducting vortex

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We study the stable configurations of a Néel-type skyrmion and a Pearl vortex interacting via stray fields in thin superconductor-ferromagnetic heterostructures. Considering that skyrmions stabilized by Dzyaloshinskii-Moriya interaction (DMI) are smaller than the Pearl length, we distinguish two scenarios: the skyrmion is attracted to (1) or repelled from (2) the center of the vortex. Introducing a novel three-parameter ansatz for the non-central-symmetric skyrmion texture, we determine the conditions for each scenario. Moreover, we predict that for the specific material parameters of the heterostructure, both attraction and repulsion can be realized depending on the initial position: the free energy can have two minima, at $a = 0$ and $a = a_0 \neq 0$, as a function of the distance a between the centers of skyrmion and vortex. The analytical results are verified by the micromagnetic simulations.

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Transport of non-equilibrium quasiparticles injected into a mesoscopic-size superconductor

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Rapid development of micro- and nanofabrication methods have provoked interest and enabled experimental studies of electronic properties of a vast class of (sub)micrometer size solid state systems. Mesoscopic scale hybrid structures, containing superconducting elements, have become interesting objects for basic research studies and various applications, ranging from medical and astrophysical sensors to quantum computing. One of the most important aspects of physics, governing the behavior of such systems, is the finite concentration of non-equilibrium quasiparticles, present in a superconductor even well below the temperature of superconducting transition. Those non-equilibrium excitations might limit the performance of a variety of superconducting devices, like superconducting qubits, single-electron turnstiles and microrefrigerators. On the contrary, in some applications, like detectors of electromagnetic radiation, the non-equilibrium state is essential for their operation. It is therefore of vital importance to study the mechanisms of non-equilibrium quasiparticle relaxation in superconductors of mesoscopic dimensions, where the whole structure can be considered as an 'interface'. At early stages of research the problem was mostly studied in relatively massive systems and at high temperatures close to the critical temperature of a superconductor [1]. Lately various phenomena have been studied in hybrid superconductor-based nanostructures enabling spatial resolution of the relaxation process [2-8]. Here we report our recent experiments indicating presence of coherent non-equilibrium transport in a NIS solid state 'double slit' interferometer-type structures.

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Multilayer hybrid structures with thin superconductive layers: from spin valve to phase logic elements

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Superconducting hybrid structures with normal metal, magnetic, and tunneling layers are being actively studied for the needs of superconducting electronics. Such structures are widely used as spin-valves, π-shifters, phase batteries, and non-volatile memory and logic elements [1]. In this case, the properties of the device mainly depend on the thickness and material parameters of the ferromagnetic layer, which brings the phase shift of the order parameter.

However, the properties of such structures also depend on the thickness of the superconducting layers. When the thickness of the intermediate superconducting layers decreases to a value on the order of the coherence length, the behavior of the structures often changes qualitatively [2].

A significant number of devices can be designed on this effect. On the one hand, changing the boundary conditions near the ferromagnetic layer and phase restoration in s-layer can cause a shift in the 0-π transition [3]. On the other hand, in some cases, a thin superconducting layer can act as a charge imbalance accumulator and change the performance of the Josephson junctions [4]. Thin superconducting layers make it possible to control the critical current in tunneling Josephson junctions, both due to the transition between 0 and pi states [5], and due to the formation of superconducting phase domains [6]. Thus, the use of thin superconducting layers in hybrid structures opens up wide possibilities for modifying existing devices and creating fundamentally new operational principles.

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Simulation of magnetization reversal by pulse of magnetic field in RF-SQUID with ϕ_0 junction

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The magnetization reversal phenomena in the superconducting quantum interference device (SQ-UID) with the single ϕ_0 junction is investigated. Dynamics of the considered system is described in the framework of Landau-Lifshitz-Gilbert equation for magnetization of the ferromagnetic layer and resistively shunted junction model for phase difference of ϕ_0 Josephson junction. Parallel MPI version of the program was developed to determine the magnetization reversal intervals. We have demonstrated the periodicity of magnetization reversal in intervals of given parameters under the action of an external magnetic field pulse. The effect of parameters on the realization of magnetization reversal is clarified. It is shown that the magnetization reversal has a periodic behavior on the amplitude of pulse and SQUID inductance. We expect the obtained results can be used in different applications of modern superconducting electronics and spintronics.

Quantum size effect in thin superconducting aluminum films

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Since the early works on superconductivity, it has been discovered that for thin films the critical temperature of transition T_c to supeconducting state can be considerably different from its value for corresponding bulk material [1]. Remarkably, as the film thickness diminishes, Tc becomes lower in some (e.g., niobium) and higher in other materials (e.g., aluminum). Despite a fairly large body of experimental data on the subject and abundance of theoretical models, to date there is no consensus in the scientific community regarding the nature of this phenomenon. Here we present theoretical and experimental study of high-quality aluminum films on various substrates. Irrespectively of the substrate material and the method of film formation, all aluminum samples demonstrate the same tendency: the thinner the film, the higher is the critical temperature. We claim that the observation is the manifestation of the quantum size effect [2].

Using the Green's function method within the BCS model, we calculate the dependence of the critical temperature of the superconducting transition on the thickness of the film. The study shows that the critical temperature increases with decreasing thickness of the Al film, which is confirmed by a set of experimental data [2].

We have obtained the dependencies of the critical temperature on the thickness of the film for clean samples and compared them with experimental data for aluminum films produced by molecular - beam epitaxy on sapphire substrates. The high quality of the aluminum films and their thickness, which exceeds the permissible limits for ultra-thin objects, allowed for the exclusion of the influence of disordered crystallites, surfaces, and substrates. It was assumed that the sample did not contain impurities, so the scattering of electrons on impurities and defects of the crystal structure was not initially considered, but the inclusion of scattering was also one of the goals of this study.

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Composite magnetic excitations in superconductor/ magnet heterostructures

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The ability to control the dispersion law of spin waves is one of the most important requirements for the engineering of magnonic devices. We show that thin-film hybrid structures consisting of a ferromagnetic (F) or antiferromagnetic (AF) insulator and a superconductor (S) or normal metal (N) have broad prospects in this field. Structures with topological superconductors are also touched upon. Due to the presence of a surface exchange interaction between the magnetic insulator and the metal, an effective exchange field is induced in the latter, which repeats the profile of the magnetization of the magnet, including the magnon. This leads to the appearance of spin polarization of the quasiparticles in the superconductor and the generation of triplet Cooper pairs in it. Moreover, the spin polarization of quasiparticles is not co-directed with the local exchange field (the effect of dynamic delay), and therefore creates a rotational moment that acts on the magnetization of the magnet. In addition, a magnon with a nonzero wave vector creates around itself a cloud of triplet Cooper pairs of electrons with equal spins, which dress it, increasing its effective mass and screening its spin.

In structures with a ferromagnet and an antiferromagnet, due to the difference in their characteristic frequencies (GHz for ferromagnets and THz for antiferromagnets), the processes described above play a different role and the effect of a superconductor on a magnet looks different. In a typical ferromagnet, spin-triplet pairs exert the main influence. They dress the magnon, increase its mass, and screen the spin. The resulting composite particle was called magnon-Cooparon [1]. For structures with an antiferromagnetic insulator, the renormalization of the magnon spectrum involves both the polarization of quasiparticles and spin-triplet pairs. Unlike a ferromagnet, the spectrum of magnons in an antiferromagnet contains two modes, which for an easy-axis antiferromagnet are degenerate in energy at zero applied magnetic field. Interaction with a superconductor leads to the removal of this degeneracy [2]. One of the interesting practical results of our work is the proposal of a method for direct measurement of the exchange field induced by a magnet in a superconductor (or a normal metal, which is considered as the limiting case of a superconductor at high temperature).

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Proximity effects in superconductor/antiferromagnet heterostructures

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The aim of this talk is to review the current state of the young subfield of superconducting spintronics - antiferromagnetic superconducting spintronics. The talk is based on the results obtained in the last two years in the Laboratory of Spin Phenomena in Superconducting Nanostructures and Devices, MIPT in collaboration with foreign colleagues and several results of other groups. It is planned to discuss the structure and properties of Néel triplet correlations induced by the proximity effect in superconductor/antiferromagnet (S/AF) heterostructures [1], mechanisms of superconductivity suppression in S/AF bilayers [2], the dependence of the critical temperature of S/AF bilayers on the width of the AF layer and the relation of these theoretical findings to the existing experiments [3]. The proximity effect at S/AF interfaces with canted antiferromagnets is also considered [4]. A unique effect of anisotropic enhancement of proximity-induced triplet correlations by spin-orbit coupling and its perspectives for superconducting spintronics are discussed. The recently predicted effects of spin-orbit coupling in Josephson structures via antiferromagnets, such as anomalous phase shift of the ground state and giant anisotropy of the critical current, are also touched upon [5,6].

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Critical temperature of superconductor/antiferromagnet heterostructures

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In this work we study theoretically two different manifestations of the sign-flipping Neel triplet correlations, which are induced in superconductor/antiferromagnet (S/AF) heterostructures by proximity effect [1]. The first one is the oscillating dependence of the superconducting critical temperature of S/AF bilayers on the length of the AF region. It occurs due to the oscillating character of the Neel triplet pair wave function, which in its turn originates from the Umklapp scattering processes at the S/AF interface. This prediction could give a possible explanation for available experimental data [2].

The second issue is the interplay of the Neel triplets with Rashba spin-orbit coupling (SOC) in thin-film S/AF structures. A unique effect of anisotropic enhancement of proximity-induced triplet correlations by the SOC is predicted. It manifests itself in the anisotropy of the superconducting critical temperature with respect to orientation of the Neel vector relative to the S/AF interface, which is opposite to the analogous effect in superconductor/ferromagnet structures. The sign of the anisotropy is controlled by the chemical potential of the superconductor and, therefore, can be adjusted in (quasi)2D structures.

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Multifractally-enhanced superconductivity in two-dimensional systems

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The multifractal superconducting state originates from the interplay of Anderson localization and interaction effects. In this talk I overview the recent theory of the superconductivity enhancement by multifractality and extend it to describe the spectral properties of superconductors on the scales of the order of the superconducting gap. Specifically, using the approach based on renormalization group within the nonlinear sigma model, we develop the theory of a multifractal superconducting state in thin films. We derive a modified Usadel equation that incorporates the interplay of disorder and interactions at energy scales larger than the spectral gap and study the effect of such an interplay on the low-energy physics. We determine the spectral gap at zero temperature which occurs to be proportional to the multifracally enhanced superconducting transition temperature. We reveal strong mesoscopic fluctuations of the local density of states in the superconducting state. We consider the case of superconducting state in the presence of spin-orbit interaction as well as near the Ising ferromagnetic quantum critical point. The talk is based on the publications [1-3].

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Electromagnetic long ranged proximity effect in superconductor-ferromagnet structures

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The spread of the Cooper pairs into the ferromagnet in proximity-coupled superconductor - ferromagnet (SF) structures is shown to cause a strong inverse electrodynamic phenomenon, namely, the long-range transfer of the magnetic field from the ferromagnet to the superconductor. Contrary to the previously investigated inverse proximity effect resulting from the spin polarization of superconducting surface layer, it exists a very generic orbital mechanism of the magnetic moment transfer from a ferromagnet to a superconductor, which is unavoidable in S/F hybrids. It is related with the fact that the common superconducting wave function in S and F (near the interface) does not permit to exclude the vector-potential of the magnetization by gauge transformation. From the experimental point of view, this phenomenon reminds the Aharonov-Bohm effect since the current inside the attached superconductor is induced by the ferromagnetic layer, which cannot create the magnetic field in the outside in the absence of such superconducting environment. At the same time, the true physical key point is that the wave function penetrating the ferromagnet is responsible for this effect. Let us stress that the characteristic length of the proposed inverse electrodynamic effect is of the order of the London penetration depth. The manifestation of this effect in S/F multilayers may lead to the generation of the relatively strong magnetic field in S layers and could explain the puzzling experimental data on the neutron scattering in Nb/Gd and other S/F superlattices.

Superparamagnetic nature of zero-dimensional superconductors within a magnetic field

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We study the thermodynamic properties of zero-dimensional Ginzburg-Landau fields. As is well known, the size of the critical region becomes larger as the dimensions of the system decrease below the coherence length. It is shown that all the superconducting effects in the zero-dimensional (0D) limit arise only from the existence of fluctuation-induced superconductivity. The electronic structure of 0D superconductors goes through several phases with qualitatively different properties. By virtue of their size, 0D superconductors are superparamagnetic under the influence of an external magnetic field, but exhibit (no remanent) magnetization when the field is removed. In zero magnetic field, the behavior of the system leads to the common Ginzburg-Landau conclusions about the ferromagnetic phase transition, with critical temperature Tc0 = 0, in accordance with the Mermin-Wagner theorem. The use of 0D superconductors in an applied magnetic field in the framework of technological applications is a novel and highly interdisciplinary field offering great potential in therapeutic and diagnostic testing, but also in the development and the design of Josephson junctions by grain junctions (onYBa2Cu3O7 compound for instance). Another aspect that is bound to contribute to the importance of this work is the emerging area of superconducting nano-electronics, such as nano-superconducting quantum interference device (nano-SQUIDs).

Landau-Zener-Stückelberg interferometry in hybrid quantum two-level systems in Josephson junction: Modeling dynamics quantum alimentation

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In this work, we study the magnetization dynamics of qubit states in a hybrid Josephson junction (JJ) where the external magnetic field is applied perpendicular to the plane self-resonant superconductor. In this regard and using the dynamics Matrix approach (DMA), the approximated quantum two-level systems are examined in detail when the dynamics of the magnetic moment is governed by the Landau-Lifshitz equation. A JJ couples the supercurrent flowing between two weakly linked superconductors to the adiabatic energy, anisotropy coefficient and phase difference between them via a current phase relation; Landau-Zener-Stückelberg (LZS) interferometry is established following the standard protocol of Landau-Zener transition (LZT) in the magnetization reversal of the spin qubit. Therefore, we ascribe our observations to the high transparency of our junctions allowing solvable LZT via the DMA using to calculate the tunneling probability of population transfer carrying 4π periodic current, which will be useful for estimating the efficiency of the protocol. Thus, the prediction of consecutive LZT modulations (strong or weak transition of current) and the conservation accuracy of LZS quantum interference patterns are identified with higher intrinsic quantum corrections considering the autoresonance with and without damping.

This work reports the application of the concepts and techniques of interferometric devices to sensing for the purpose of performing magnetic resonance experiments in a novel regime, where quantum fluctuations of the microwave field have a major impact on the sensitivity of interferometry and on spin dynamics.

Peculiarities of the density of states in SN junctions

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We study the density of states (DoS) ν; (E) in a normal-metallic (N) film contacted by a bulk superconductor (S). We assume that the system is diffusive and the SN interface is transparent. In the limit of thin N layer (compared to the coherence length), we analytically find three different types of the DoS peculiarity at energy equal to the bulk superconducting order parameter $\Delta_0(i)$ In the absence of the inverse proximity effect, the peculiarity has the check-mark form with ν;($\Delta_0(i)$)=0 as long as the thickness of the N layer is smaller than a critical value. (ii) When the inverse proximity effect comes into play, the check-mark is immediately elevated so that ν;($\Delta_0(i)$)>0. (iii) Upon further increasing of the inverse proximity effect, ν; (E) gradually evolves to the vertical peculiarity (with an infinite-derivative inflection point at E=$\Delta_0(i)$). This crossover is controlled by a materials-matching parameter which depends on the relative degree of disorder in the S and N materials.

Magnetic and optical absorption properties of RbCl quantum dot nanostructure

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Using the Landau and Pekar method, we studied the magnetic, electromagnetic field, Coulomb impurity and electron-phonon coupling effects on the properties of the optical absorption coefficient in Rubidium Chloride (RbCl) quartic quantum dot. Firstly, the calculation of the ground and first excited state energy has been done. Secondly we have calculated one of the indispensable physical quantities in the analysis of the optical properties related to the transition of energy states inside the structure: the absorption coefficient, the magnetic properties. The results shown that, the electric and magnetic field, the confinement length and impurity considerably change the optical absorption coefficient. The ratio of the contribution of one phonon oscillation strength to the contribution of the zero phonon is very considerable for smaller size structure, increase by the electric field but decrement by the magnetic field and impurity. We have demonstrated that the RbCl quartic quantum dot with smaller size and in the presence of the electric field grows of the optical absorption coefficient but in the presence of magnetic field and impurity diminishes of the optical absorption coefficient. This work highlights the importance of studying the absorption properties and magnetic properties of materials before their use in the manufacture of devices.

Keywords:
Electromagnetic field; Optical absorption; Polaron; RbCl quartic quantum dot; Coulomb impurity.

Transport properties of various types of mesoscopic planar S-N/ F-S Josephson junctions with a strong ferromagnet

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We study superconducting transport properties of planar submicron-size S-N/F-S Josephson structures in the resistive state with the perpendicular ferromagnetic electrode in the applied magnetic field and with the injection current through the weak link. The splitted superconducting gap peculiarity was observed in the differential resistance characteristics. The splitting increases with the further increase of the injection current. This effect can be caused by the spin injection into the weak link from the F -electrode and a change of the magnetic state of the F layer. The latter is confirmed by the differential resistance measurements in the external magnetic field. We have demonstrated that the splitted peculiarity is converted to a single peak at a coercive applied field corresponding to zero magnetization of the F-layer.

Manifestations of unconventional pairing symmetry in superconducting hybrids

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Superconducting states with broken time-reversal symmetry may arise in structures with nontrivial topological properties and are currently of high interest from fundamental and applied points of view. We will discuss theoretical basis for the description of interfaces between unconventional superconductors (S) and normal metals (N). We will present the results for electronic and spin transport in multiterminal S/N hybrid structures [1-3]. Technically, the derivation of boundary condition for the Nambu-Keldysh quasiclassical Green's functions at the S-N interfaces will be outlined. Of particular interest is application to superconductors with mixed s + p-wave superconducting pairing symmetry, including the cases of chiral and helical p-wave state in two dimensions, as well as the so-called Balian-Werthamer state in three dimensions. The local density of states, charge and spin conductance will be discussed. The cases will be identified when the proximity induced pairing in N has odd-frequency spin-triplet s-wave symmetry. This state is characterized by the existence of a robust zero energy Andreev bound state.

Within the developed approach, three- and four-terminal S/N structures are investigated where the superconducting potential is a mixture between s-wave and p-wave potentials. The ways are proposed to determine whether S has a mixed pair potential and to distinguish between chiral and helical p-wave superconductivity. In this case a difference in conductance for electrons with opposite spins arises if both an s-wave and a p-wave components are present, even in the absence of a magnetic field. It is shown that a setup containing two SN junctions provides a clear difference in spin conductance between the s + chiral p-wave and s + helical p-wave symmetries. Further, we propose new approach to distinguish p-wave from s-wave symmetry by measuring conductance a four terminal junction consisting of S and N terminals. The N-terminals are used to manipulate the energy distribution functions of electrons in the junction in order to control the charge transport. It is shown that the differential conductance of junctions containing p-wave and s-wave superconductors is distinctly different, thus providing experimental test to detect potential p-wave superconductivity.

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Dynamics of Josephson vortices in high-frequency devices

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Currently, the Josephson junction (JJ) is widely used as the main element of superconducting logic systems. Magnetic flux quanta, called Josephson vortices (JVs), can penetrate into sufficiently long junctions, which can be used to transmit and store information. In this work, we investigate a system consisting of a long Josephson junction integrated in the coplanar resonator. This allowed us to measure the states of the JJ with a microwave current of small amplitude, without making changes to the junction itself. We were able to detect the entrance and exit of JVs and detect the hysteresis effect associated with the surface barrier for vortices. Our numerical simulation of the long JJ confirmed the existence of hysteresis in the same magnetic fields as in the experiment. We experimentally demonstrated switching between a state without vortices and with a single vortex in the junction. Based on this effect we propose the concept of cryogenic memory. (RSF 23-72-30004).

Various models of superconducting spin valve

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Here two different models of superconducting spin valve designs were investigated. The first model of F1/F2/S structures, where the Heusler alloy $\mathrm{Co_2Cr_{1-x}Fe_xAl_y}$ prepared at different substrate temperatures was used as both ferromagnetic layers. For this type of samples, it was possible to observe a huge triplet contribution to the effect of the superconducting spin valve ΔT_c^{trip} of more than 1 K. The second model of F1/S/F2 structures, where additional insulating layers are introduced at the boundaries of the ferromagnet/superconductor and superconductor/ferromagnet sections. For this type of samples, it was possible to observe the full effect of a superconducting spin valve with a value of $\Delta T_c \sim 0.2$ K.

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Collective excitations in superconducting systems at the magnetic surface of 3D TI

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Recently, helical state became an active area of research in the field of superconductivity. Such an interest is driven by the possibility of using the helical state for the superconducting diode effect realization [1]. In the present research we study the superconducting state caused by the helical state, which emerges in the system due to the presence of the magnon. For this purpose, we consider the effective model of topological insulator surface with an s-wave superconductivity and induced magnetization. Such systems can be experimentally designed in the forms of hybrid structures or synthesized as materials with intrinsic properties [2]. Employing the Keldysh formalism for the quasiclassical Green's functions in the diffusive limit we obtain fully self-consistent solution of the problem in the presence of the weak magnon. We demonstrate that in the system under consideration the magnon has a direct impact on the pair potential, i.e. it couples to the pair potential in the first order. This leads to the appearance of the collective excitations at the certain parameters of the spin wave. Furthermore, we reveal the effect of the helical state on the collective excitations and other properties of the system.

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Topological Hall effect in van der Waals Magnets

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Recently non-chiral spin structures on the surface of the van der Waals (vdW) magnets have been observed down to monolayers. We provide a Hamiltonian to analyze the electronic properties of these materials. The Hamiltonian takes into account the arbitrary background spin structure and the large atomic spin S of the materials. The large spin-S treatment is necessary as magnetic atoms of the vdW magnets can have spin $S > 1/2$. In this work the Hamiltonian is solved for the spin spirals with azimuthal and polar degrees of freedom – this spin structure was recently observed in Fe_3GeTe_2. We methodically analyze the Hamiltonian for both integer and half-integer spins in the honeycomb lattice. It shows emerging topological Hall effect, irrespective of the spin. The Chern number, hence the topological phase, depends on the spin S, and interestingly only on the azimuthal angle of the spin vector. These results will be useful for the design of the topological electronics devices based on vdW magnets.

We use the spin structure:

$$\vec{S}_i = S\left(\sin\vec{q}_1\vec{r}_i\cos\vec{q}_2\vec{r}, \sin\vec{q}_1\vec{r}_i\sin\vec{q}_2\vec{r}_i, \cos\vec{q}_1\vec{r}_i\right).$$

Here, $\vec{q}_1$ and $\vec{q}_2$ are the spin wave vectors, r_i is the position vector. $S = 1/2, 1, 3/2, \ldots$ is the highest spin state of the background atoms. The three terms in spin configuration represent the three components of the spin vectors, $\vec{S}_x$, $\vec{S}_y$, and $\vec{S}_z$. If this spin configuration is mapped to a Bloch sphere, then $\vec{q}_1\vec{r}$ and $\vec{q}_2\vec{r}$ represent the polar angle and the azimuthal angles respectively. Using the above spin configuration we analyze the topological Hall effects for integer and half-integer spins.

Quantum Hall Bogoliubov interferometer

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Chiral one-dimensional transport of quasiparticles along the boundary of a gapped two-dimensional electron system (2DES) is a fundamental aspect of the quantum Hall effect. A combination of phase-coherent ballistic propagation over large distances together with a controllable backscattering by gate-defined constrictions result in a plethora of quasi-particle interference phenomena in quantum Hall edge channels. Matching these unique capabilities with a superconducting proximity effect may greatly advance the research in semiconductor- superconductor hybrids.

In this work, I propose a quantum Hall Bogoliubov interferometer, that is a modification of a Fabry-Perot type interferometer with a superconducting terminal inside. This geometry enables a fine tuning of the local and non-local normal and Andreev scattering amplitudes by means of the Aharonov-Bohm (AB) phase and constrictions defining the interferometer loop. The proposed interferometer represents a versatile three-terminal NSN device that enables full control over the non-local charge and heat quasiparticle transport, including a resonant enhancement of an arbitrarily small Andreev reflection probability up to 1.

Strontium Iridate as a barrier material for high-T_c–low-T_c Josephson junctions

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Strong spin-orbit interaction in iridium oxides attracts much interest for applications as barrier material in superconducting heterostructures. Iridium has a large atom number and in iridates the energy of the spin-orbit interaction (SOI) is so large as 0.5 eV [1]. Sr_2IrO_4 (SIO4) could be described as insulator with a band gap of 100 meV, and as well as variable range hopping conductor with a localization radius $a \approx 0.1 - 0.3$ nm [3]. If SIO4 layer placed between superconductors the strong enhancement of triplet superconducting current due to the SOI has been predicted [4].

In our study two models of charge carrier transport were used for SIO4 films. The first one is the thermal activation, when the temperature dependence of the film resistivity obeys the formula

$$\rho(T) = \rho_0 \exp\left(\frac{\Delta E}{kT}\right),$$

where ΔE is the band gap, ρ_0 is an experimental constant, and k is the Boltzmann's constant. The approximation of the resistivity versus temperature dependencies of SIO4 films gives ΔE values of 200 – 230 meV [5]. Another model is a three-dimensional variable-range hopping conduction (VRH), when the temperature dependency of the resistivity may be written as

$$\rho(T) = \rho_0 \exp\left[\left(\frac{T_0}{T}\right)^{1/4}\right],$$

where T_0 is VRH temperature. By the VRH approximation temperatures $T_0 \sim 5 - 10 \times 10^7$ K were estimated for the films studied [5, 6]. It is not clear what model: thermal activation or VRH is more suitable for dependencies of the SIO4 films. Similar results were obtained elsewhere: temperature dependencies of SIO4 films were approximated by thermal activation for films with a 100 nm and large thickness and by VRH for thinner ones [3].

Three layer heterostructures which consists of YBaCuO /SIO4/ Au-Nb were investigated. For the layer SIO4 the barrier heights were estimated from differential conductivity versus voltage dependencies as of 100 – 250 meV [7]. Critical current density J_C and normal surface resistivity $R_N S$ dependencies on barrier thickness t were obtained for supeconducting heterostructures YBaCuO /SIO4/ Au-Nb. From exponential fits of the dependences localization radii of charge carriers α in the SIO4 layer were calculated as 1 – 2 nm. From the formula

$$E = h^2/(8\pi^2 m\alpha^2),$$

where E is the barrier height, m is electron mass, h is the Plank constant, we calculated the barrier height in the SIO4 layer. Barrier heights of 10 – 40 meV were obtained.

In conclusion electrical current transport was investigated both in Sr2IrO4 thin films and in heterostructures with SIO4 barrier layers. The films of SIO4 are an insulating nature. The band gap in SIO4 varied in wide range of 10 – 200 meV which is dependent on deposition condition of thin films or depends on nature of interface with superconducting electrodes.

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Tunnel magnetoresistance and exchange interaction in superferromagnets

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Advances in micro- and nano-technologies have led to the widespread use of spintronic magnetoresistive (MR) sensors for both recording and non-recording applications. Such ultramodern magnetoresistive sensors have high sensitivity of the detected ultra-weak fields, which meet the requirements of intelligent sensor applications in the fields of the Internet, mobile devices, space technology, aeronautics, magnetic flux leakage, domotics, environment, healthcare and medicine. Moreover, their adaptability and miniaturization, simple integration and cost-effectiveness make these sensors uniquely competitive in terms of spread applications and production.

In this work, ensembles of superparamagnetic particles (SPM) imbedded in an insulator or semiconductor are considered. At a sufficiently high concentration of SPMs these metamaterials show superferromagnetic properties and can be used as MR sensors. We consider the electric current between the SPM particles and show that the resulting tunneling MR increases as the size of the SPM decreases.

Disorder-induced trapping and antitrapping of vortices in type-II superconductors

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We study the features of the superconductivity nucleation and vortex configurations in superconductors with modulated disorder. Using the Ginzburg-Landau–type theory with spatially varying diffusion coefficient, we uncover and explain the switching between the vortex-defect attraction to the repulsion upon the increase in the external magnetic field. It is shown that for rather weak applied magnetic fields, a superconducting nucleus localized near the region with the suppressed diffusion coefficient possesses a nonzero vorticity whereas the increase in the magnetic field can lead to a transition into the state with zero winding number. We demonstrate the manifestations of this switching phenomenon in superconductors with a large number of defects by performing numerical simulations of the vortex structures in superconductors with periodic spatial profiles of the diffusion coefficient. The obtained results clarify the physics of the vortex arrangement in several classes of the superconducting materials including one-dimensional superlattices and nanopatterned superconductors with regular arrays of the defects characterized by the increased concentration of nonmagnetic impurities. Based on analytical estimates within the framework of the Ginzburg-Landau theory, we show that the predicted switching in the pinning mechanism can manifest itself in the change of the slope of the critical current as a function of the external magnetic field.

The work involving the analysis of the phase diagrams in superconductors with modulated disorder was supported by the Russian Science Foundation (Grant No. 21-12-00409). The work involving the analysis of the magnetic field behavior of the critical current was supported by the State Contract of Ministry of Science and Higher Education of Russian Federation Grant No. 075-03-2022-106 (Project No. FSMG-2023-0011) of Moscow Institute of Physics and Technology

Effect of electromagnetic radiation magnetic component on φ_0 Josephson junction

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In this work we study the influence of the microwave radiation magnetic component on electric current and magnetization dynamics of φ_0 Josephson junction. Previous studies show that the effect of radiation on SFS junctions leads to a number of interesting phenomena that can be used in future electronic devices. To describe the coupled dynamics of ferromagnet magnetic moment and electrical current in the presence of external radiation we used the Landau–Lifshitz–Gilbert equation and the Resistively Capacitance Shunted Junction model. Derived system of nonlinear equations is investigated numerically. It is shown that the magnetic component of external radiation leads to the appearance of integer and half-integer current steps in IV characteristics, splitting of magnetization resonance peaks, and new frequencies in the magnetization dynamics spectrum. There is also a dip in the resonance magnetization curve, the area of which coincides with the current step in the IV characteristics. Magnetic moment precession mechanism and IV characteristics are investigated at different parameters of φ_0 junction and microwave radiation. The analytical solution of the linearized equations of magnetization dynamics under the influence of the radiation magnetic component and superconducting current is also presented. This solution gives the relations of the frequencies determining the positions of the resonant peaks of the magnetization dynamics spectrum.

Experimental evidence for both triplet and singlet long-range supercurrents through a strong ferromagnet

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Superconductor/ferromagnet (S/F) heterostructures are promising candidates for the creation of superconducting spintronics. Although supercurrents through F were reported many times, it is difficult to judge about their nature (singlet or triplet). First, even spin-singlet current can flow over long ranges in clean or weak ferromagnets [1]. The singlet current is reduced in strong F, which should be materials of choice for a critical test. Second, the supercurrent strongly depends on a usually unknown domain structure in F, flux quantization in S, both influenced by size and geometry [2]. This uncertainty can be obviated in nanoscale devices with mono- (or few) domain F layers and with the flux-quantization field larger than the coercive field. Finally, the long-range triplet current should appear only in the noncollinear magnetic state. Therefore, unambiguous identification of the pairing order is only possible if the micromagnetic state of the actual device is known. It is not sufficient to analyze similar large-area heterostructures because their magnetic properties (coercive fields, domain structure, shape anisotropy) would be different from a nanodevice. To prove (disprove) the triplet nature of supercurrent, it is necessary to demonstrate its correlation (anticorrelation) with the noncollinear state. In the end, it is all about having an in situ control over the micromagnetic state of the studied nanodevice.

This presentation gives an overview of our recent works [1-4], in which we aim to develop in-situ characterization methods for analysis of S/F/S Josephson junctions, SF1NF2S pseudo spin-valves, and S/F multilayers, containing strong undiluted Ferromagnets Ni and Co. Along with standard transport characterization techniques, such as magnetoresistance and Hall effect, we also demonstrate novel techniques such as absolute Josephson fluxometry and the first-order-reversal-curves (FORC) analysis. This allows unambiguous identification of micromagnetic states in S/F nano-devices and demonstrate presence of both singlet and triplet long-range supercurrents through strong ferromagnets.

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Resonance phenomena in the system of nanomagnet - Josephson junction under an external periodic signal

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We demonstrated resonance effects in a system of nanomagnet coupled to the Josephson junction under the influence of external periodic drive. We show that the applied periodic drive brings to the appearance of additional resonance peaks, which positions determine by the driving frequency. The heights of the resonance peaks depend on the driving amplitude as a Bessel function. We develop a thorough analytical description that allows to classify all possible resonances arising in the system. The obtained result provide a method for controlling the resonance properties of the system. It has been demonstrated that by changing the amplitude of periodic drive it is possible to suppress the main ferromagnetic resonance and at the same time excite a new one with required amplitude and frequency. We consider that the obtained results open a wide field of research and applications related to the resonance properties of hybrid structures. Such a realization might play a crucial role in quantum information processing and spintronics.

Effect of superconductivity on non-uniform magnetization in dirty SF junctions

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We consider a junction between a bulk superconductor and a thin ferromagnetic layer on its surface (SF junction) with nonuniform magnetization. In the absence of the superconductor, the most energetically favorable state of the ferromagnet is uniform. On the other hand, Cooper pairs from the superconductor can more efficiently diffuse into the ferromagnet if its magnetization changes in space rapidly enough [1, 2]. We demonstrate that the competition between these two effects leads to the second order phase transition between uniformly magnetized and helical states of the ferromagnet.

We assume the junction is in the dirty limit ($\Delta\tau \ll 1$) and the ferromagnetic layer is sufficiently thin ($d \ll \sqrt{D/\{\Delta, h\}}$). In addition, we also assume a tunnel boundary between the superconductor and the ferromagnet. These assumptions allow us to describe the hybrid system in the framework of the 2D Usadel equation.

We have minimized the free energy of the system allowing for an arbitrary nonuniform magnetic state and constructed a Landau functional expanding the free energy in powers of magnetization gradients. This calculation establishes conditions for the phase transition between uniform and helical magnetic states. In particular, we have observed a quite unexpected "resonance" phenomenon: when the exchange energy of the ferromagnet equals the proximity-induced superconducting order parameter, transition to the helical state occurs irrespective of the value of ferromagnetic stiffness.
In addition to describing the phase transition, our method also allows exploring a general case of arbitrary system parameters. In particular, we can determine the magnitude of the helical state wave vector far from the phase transition. This will be the subject of our future studies.

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Topological Josephson junction in transverse magnetic field

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Majorana edge zero modes appear in a topological Josephson junction between two superconducting contacts on top of a 3D topological insulator. We consider a setup where Majorana bound states are point-like structures bound to Josephson vortices in an external magnetic field perpendicular to the surface. Their position can be controlled, and they can be used for topological quantum operations, using hybridization of nearby modes. We analyze hybridization and find that it vanishes at vanishing chemical potential due to symmetries of the problem. This ensures extra protection of the Majorana zero modes and provides methods to control the inter-mode tunnel coupling for quantum-information applications.

The fate of non-magnetic defects in topological superconductors with and without TRI

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In this work, we study the effect of non-magnetic disorder on topological superconductors that preserve and break the time-reversal symmetry. By modeling two different types of random disorder we show that, in direct contradiction to naive expectations, non-magnetic disorder has a detrimental effect on the topological phase by quickly closing the bulk gap. In sharp contrast, the situation is essentially opposite for the trivial superconducting phases and they remain stable against non-magnetic disorder. At the end, we provide a comprehensive explanation for this observation based on the appearance of impurity-induced subgap states in the topological phase and its absence in the trivial phase.

Highly efficient multimode superconducting quantum memory

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Fault-tolerant quantum computing and quantum internet require quantum memory as an essential building block of a future quantum information processing platform. Superconducting circuits quantum electrodynamics (cQED) is among the leading realizations of intermediate-scale quantum computers. Meanwhile there is a strong motivation to break the wall of nearest-neighbor qubit coupling using enhanced cQED architecture with integrated quantum memory. Moreover, it would allow to extend limited coherence time of the superconducting qubits, implement complex quantum algorithms and hardware-efficient quantum error correction. Compared with traditional superconducting qubits, high quality factor resonators have a superior potential for quantum state storage due to their impressive lifetime efficient thermalization, no extra fridge control lines and ability to couple multiple qubits.

Our quantum storage device consists of one common resonator that interacts with eight internal superconducting resonators and coupling waveguide. We adopt a small difference in Δ of 0.5 MHz for two groups of resonators to select two frequency modes for storage and separate them in time domain. We present normalized time-domain data at the outputs of both memories for a input pulse with large average photon number. The first memory cell irradiates 75±8% of the input power in the first echo after 277 ns, while the second memory cell outputs 52±5.7% of input power in its first echo after 310 ns. Next we perform experiments on a storage of microwave pulses at a single photon level in the first quantum memory cell. We gradually decrease the intensity of the signal pulse and observe a reduction in the efficiency from 75±8% to 60±6.4% in single photon regime.

We confirm a noiseless character of our quantum storage by performing coherent state quantum process tomography on our memory with a single microwave mode. From the reconstructed process tensor, the single photon power efficiency is estimated to be 60 ± 3% that is consistent with heterodyne measurements at low intensity.

In conclusion, we experimentally demonstrate microwave quantum storage for two spectral modes of microwave radiation in on-chip system of eight coplanar superconducting resonators. Single mode storage shows a power efficiency of up to 60±3% at single photon energy and more than 75±8% at higher intensity. The noiseless character of the storage is confirmed by coherent state quantum process tomography.

Nonlocal interlayer pairing and induced superconductivity in layered hybrid structures

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We study the influence of the spin-triplet interlayer electron on the induced superconductivity in two-dimensional electron gas (2DEG) proximity coupled to a conventional superconductor. Using the mean-field approximation for the interlayer interaction, we demonstrate that the spin-triplet interlayer pairing results in the appearance of the odd-frequency component of the pairing correlations in 2DEG and gives rise to an additional spin splitting for quasiparticles. It is shown that the manifestations of this phenomenon include the multi-peak structure in the density of states of 2DEG, the suppression of the Meissner response of the induced superconducting correlations in the low-temperature regime or even the appearance of an additional paramagnetic contribution from 2DEG to the screening properties of the hybrid structure.

Increasing the reproducibility of Al/AlOx/Al Josephson junctions for superconductor quantum circuits

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The most commonly used physical realization of superconducting qubits for quantum circuits is a transmon. There are a number of superconducting quantum circuits applications, where Josephson junction critical current reproducibility over a chip is crucial. Here, we report on a robust chip scale Al/AlOx/Al junctions fabrication method due to comprehensive study of shadow evaporation and oxidation steps. we investigate e-beam evaporation of bottom Al electrodes with deposition rate in the range of 0.2–1.5 nm/s, electrode thickness from 15 to 45 nm (the lower limit was determined by the film continuity condition at room temperature), and deposition angle from 0° to 60°. Results show an extremum that corresponds to minimum RMS surface roughness and line edge roughness (LER) of the bottom electrode. This dependence is typical for a wide range of deposition angles (from 0° to 60°). Deposition rate plays an important role in controlling adatoms surface diffusion and relocation. Rapid arrival of new particles (adatoms and cluster) could bury and interfere with particles diffusing on the substrate surface or thin film surface. That is, the surface roughness and line edge roughness of the film increases with increasing deposition rate. One can use the combination of small deposition angle and thickness to fabricate high quality (RMS ~ 1 nm, LER < 1.3 nm) bottom JJ electrode. The influence of oxidation method, pressure and time on critical current reproducibility is determined. We experimentally demonstrated the influence of the oxidation method on the critical current reproducibility. Up to 14 % better critical current reproducibility across the chip was observed with the static oxidation method at low oxidation pressures (less than 0.1 mbar). It can be explained by oxygen leaking into the chamber during the oxidation process at very low pressures. Transition to dynamic oxidation allowed reducing the critical current reproducibility over a chip for the range of oxygen pressures from 0.001 to 0.1 mbar. With the proposed method we demonstrate Al/AlOx/Al junction fabrication with the critical current variation ($\sigma/\langle Ic \rangle$) less than 3.9 % (from 150×200 to 150×600 nm^2 area) and 7.7 % (for 100×100 nm^2 area) over 20×20 mm^2 chip. The proposed approach and optimization criteria can be utilized for a robust wafer-scale superconducting qubit circuits fabrication.

Impedance-matched Josephson parametric amplifier; bandwidth optimization by SNAIL parameters variation

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Parametric amplifiers have become key components in quantum information processing due to their near quantum-limited noise performance. Those devices are used as the first stage of the low-noise amplification schemes defining primarily the overall system noise and signal-to-noise ratio. Broadband Josephson parametric amplifiers are the only tools to perform single-photon power measurements of microwave and optical signals, quantum metrology, and dark matter search. In quantum computing, it has been used for high-fidelity single-shot readout of superconducting qubits, real-time quantum feedback control, and generating squeezed quantum states.

In this work, we present a quantum-limited 3-wave mixing impedance-matched JPA consisting of a SNAIL array with an on-chip two-section microstrip impedance transformer. It operates in reflection mode when the input signal reflects off, generating the amplified output signal with a gain of more than 17 dB and idler tone. To improve the dynamic range of our degenerate parametric amplifier we use the SNAILs, which provide the flexibility in optimizing a 3-wave-mixing amplification process, while simultaneously minimizing a 4-wave-mixing Kerr nonlinearity suspected to cause amplifier saturation. The substitution of a SNAIL array for each of the junctions in the JPA SQUID increases the saturation power of the amplifier (scales as Ic2/Q3, where Ic is the critical current of large Josephson junction in a SNAIL loop and Q is the coupled Q-factor) while keeping the total inductance of the device roughly the same.

The IMPA fabrication includes a two-step process: (I) SNAIL and impedance transformer pattering with double-angle evaporation and lift-off, and (II) wafer backside metallization. We demonstrated an average gain of 15 dB with a bandwidth over 600 MHz at the central resonance frequency of 6.4 GHz, which corresponds to the design frequency. We demonstrate increasing the gain and bandwidth with SNAIL assymetry increasing. The noise temperature was estimated to be close to the standard quantum limit with the saturation power in the range of [−97, −100] dBm.

Superconducting hybrid structures with spin-orbit interaction

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Superconducting electronics is widely used in many areas, from the implementation of quantum computers, to the creation of terahertz detectors. Further miniaturization of the element base of superconducting logic is faced with the need to take into account the features of the electronic team in hybrid structures. Thus, the spin-orbit interaction that occurs in heavy metals or in 2D structures can significantly affect the dynamics of superconducting devices. And ferromagnetic systems with non-collinear magnetization have prospects for the implementation of memory elements. In this work, we studied the S-N(SO)-F structure, which is a series-connected S-superconductor, a thin film of N-normal metal with spin-orbit (CO) interaction, and an F-ferromagnet with an arbitrary direction of magnetization. To analyze the system, the Usadel equations were used, on the basis of which the numerical calculation tools were used to find the value of the order parameter at the free boundary of the S-layer. The study analyzed the dynamics of Green's functions: the S-layer pumps a ferromagnet with singlet superconductivity; in the F layer, Cooper singlet pairs are depaired into triplet pairs under the influence of the exchange energy h; further, penetrating into the N-layer, the triplet functions mix with each other and begin to decay, which leads to an increase in the singlet function and, ultimately, an increase in the order parameter. Thus, CO interaction can prevent the destruction of superconductivity by a ferromagnet. Moreover, the maximum effect is achieved at those magnetization rotation angles co-directional with the direction of the spin-orbit interaction vector. By varying various parameters, such as the lengths of the layers, the value of the exchange energy, and the temperature of the system, it was possible to detect a significant restoration of superconductivity upon a change in the orientation of the magnetization of a ferromagnet, which may be promising for the implementation of a spin valve. Also in the work, a comparison was made with the implementation of a spin valve based on the S-F'-F system with two non-collinear ferromagnets. It was shown that such a system, upon magnetization reversal, can give a much greater effect of superconductivity recovery, but from a technical point of view, it is more complicated to manufacture and control.

Topologically protected qubit in helical crystal

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We consider helical crystal (HC): superlattice based on tunnel-coupled edge states arising in an array of ordered antidots (AD) in a two-dimensional topological insulator (motivated by experimental work [1]). Individual AD has been previously studied [2]. The band structure of the HC is calculated for a 1D array placed in a magnetic field. It is shown that for integer and half-integer values of the magnetic flux through the AD, the band gaps of the HC are closed. With a small deviation of the magnetic flux from these values, massive Dirac cones appear, the energy distance between which can be controlled by a purely electrical way (gate electrodes).

Also, we study the electron-electron interaction in such system. It leads to the multicritical behavior. There is completely unstable multicritical fixed point separating three phases: “independent rings”, “independent arms”, and “spin-flip chiral channels”.

Most prominent that in the presence of defects in the HC. For example, near the wall between the ring regions with large and small radii, a pair of localized states (a topologically protected qubit) arises with energies lying in the middle of the band gaps of massive Dirac cones [3]. The splitting between energy levels of a qubit can be controlled both by a magnetic field and purely electrically. The possibility of purely electrical high-temperature control of the qubits opens a wide avenue for application in the area of quantum computing.

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Influence of superconductivity on the magnetic state of thin layers of rare-earth metals

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The contact of superconducting (S) and ferromagnetic (F) materials leads to various interesting interactions called proximity effects. Heterostructures of thin alternating S and F layers are the best platform for such studies. The influence of magnetism on superconductivity is manifested in the phase change of the superconducting wave function ("π-phase superconductivity") and spin-triplet Cooper pairing. The effect of superconductivity on the magnetic state is less studied. Structures with niobium and rare-earth metals (RE) can be promising systems for such researches. The advantage of such systems is the high transparency of the interface, which simplifies penetration of superconducting correlations in F system. REs also have weak ferromagnetism, which equalize energies of both interactions and facilitates the effect of proximity. In this work, holmium and dysprosium, which have a helimagnetic noncollinear structure, were used as REs. We demonstrated changes in their magnetic ordering under the influence of superconductivity using polarized neutron reflectometry.

Superconducting current in mesa structures with an interlayer of strontium iridate - strong spin-orbit interaction material

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Сверхпроводящий ток в меза структурах с прослойкой из иридата стронция – материала, обладающего сильным спин-орбитальным взаимодействием**

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Представлены результаты экспериментального исследования джозефсоновских меза-структур с барьерной прослойкой из иридата стронция Sr_2IrO_4 с толщинами 5 и 7 нм. Тонкопленочные меза-структуры $NbAu/Sr_2IrO_4/YBa_2Cu_3O_{7-}$ можно представить как S1-I-S2, где S1,S2 – сверхпроводники NbAu и $YBa_2Cu_3O_{7-}$, прослойка I – антиферромагнитный изолятор Sr_2IrO_4, обладающий сильным спин-орбитальным взаимодействием с энергией порядка 0.5 эВ. В докладе будут представлены сведения по технологии роста эпитаксиальных гетероструктур $Sr_2IrO_4/YBa_2Cu_3O_{7-}$ и по методике изготовления гибридных планарных меза-структур на их основе. По измерениям ВАХ на постоянном токе было обнаружено возникновение пика проводимости (zero bias conductance peak), объясняющееся возникновением низко-энергетических уровней на границе раздела $Sr_2IrO_4/YBa_2Cu_3O_{7-}$. Под воздействием СВЧ облучения в мм диапазоне обнаруживались, помимо основных, дробные ступени Шапиро, свидетельствующие об отклонении ток-фазовой зависимости от синусоидальной и об образовании второй гармоники, что нельзя объяснить d-волновой симметрией для c-ориентированного $YBa_2Cu_3O_{7-}$ сверхпроводника. В эксперименте наблюдается асимметрия в величинах критического тока, амплитуд ступеней Шапиро, а также магнитополевых резонансных ступеней Фиске.

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Multiple Andreev reflections in diffusive SINIS and SIFIS junctions

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In recent years, transport properties of superconductive junctions have been an important topic. One of the proximity effects detected in such structures, is the Andreev reflection (AR), which we study. In this work, we consider long diffusive superconductor-normal metal-superconductor junctions with low transparency interfaces, at sufficiently low temperatures, $E_{\mathrm{Th}} \ll T \ll \Delta$. In our computation, we take into account proximity effects alongside with inelastic scattering processes in a normal region, which leads to thermalization in the weak link. Our calculations reveal that current-voltage characteristic of such a junction has peculiarities at specific values of the voltage bias, corresponding to AR. Furthermore, we find that weak exchange field in normal region produces linear splitting of these peculiarities. We assume that such splitting is a direct consequence of the thermalization in the normal region, therefore we propose a modification of the Blonder-Tinkham-Klapwijk semiconductor scheme of calculating voltages, corresponding to AR.

Universality of the spectrum of multiterminal SNS-junction

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In 1962, B.Josephson predicted the effect of nondissipative current flow through a weak bond between two superconductors in the absence of voltage. This phenomenon is still the basis for many theoretical and experimental studies. Recently, Josephson junctions with a large number of $(M > 2)$ terminals based on normal metals, semiconductors, and superconductors have attracted great interest.

In our talk we consider $M-$terminal Josephson junction and discuss universality of Andreev bound state (ABS) spectra. Is it possible to calculate ABS if one knows transmission probabilities? This question is actual since according to Landauer formula the last quantities can be reconstructed from the conductance measurements of the system in the normal state. We demonstrate that under some conditions the answer to this question is positive and spectra of ABS posess universality. It means that junctions with different reflection and transmition phases may have the same spectra.

Thermal quantum correlation in two superconducting qubits

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The thermal evolution of local quantum uncertainty (LQU) is studied in two superconducting qubits. The Hamiltonian parameters such as Josephson and mutual coupling energies can cause LQU to increase for specific values. However, the temperature has a destructive effect on LQU. The results can be compared with experimental works.

Static and dynamic inverse proximity effect in superconductor/ ferromagnet hybrids

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In this work we theoretically studied the influence of magnetization orientation and dynamical precession in a ferromagnetic insulating material (FI) on the superconducting condensate properties of the adjacent superconducting layer (S), i.e. the inverse proximity effect (IPE). The static IPE exhibits in the induced magnetization in the superconductor and in its electron density of states, the dynamical IPE also produces a spin current via spin pumping through the FI/S interface.

The goal of the present work is the description of the dynamics of the spin of the superconducting condensate inside a superconducting film, which is in contact with a ferromagnetic insulating layer under the conditions of the ferromagnetic resonance (FMR). It is calculated the spin current and the induced magnetization not only at the interface of the S/FI hybrid structure, but also inside the superconducting film. The space distributions and the frequency dependence of these values are presented. The induced magnetization weakly depends on the FMR precession frequency, in contrast with the spin current. It is also shown that the increasing of the magnetization precession frequency can drastically change the spin polarization distribution of the quasiparticles [1].

The static magnetization and the spin resolved density of states in a superconductor induced due to the IPE is also studied in bilayers containing a superconductor and a ferromagnetic insulator or a strongly spin-polarized ferromagnetic metal. The study is performed within a quasiclassical Green function framework, wherein Usadel equations are solved with boundary conditions appropriate for strongly spin-polarized ferromagnetic materials. A comparison with recent experimental data is presented. The singlet to triplet conversion of the superconducting correlations because of the proximity effect with a ferromagnet is analyzed. The interesting and unexpected results are the non-monotonous behavior of these values inside the superconducting film and an optimal IPE at a small spin-mixing parameter [2,3].

These results may deepen our knowledge of effects appearing in superconducting spintronics devices and open new perspectives of spin currents and spin density transfer in such devices.

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Обратный эффект Фарадея в сверхпроводниках с конечной щелью в спектре возбуждений

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В работе построено аналитическое описание обратного эффекта Фарадея (генерации не зависящего от времени магнитного момента под действием циркулярно поляризованной электромагнитной волны) в мезоскопических сверхпроводящих образцах с конечной величиной щели в спектре возбуждений. В рамках модифицированной нестационарной теории Гинзбурга–Ландау (уравнений Крамера–Уоттс-Тобина) для тонких сверхпроводящих дисков показано, что в широком диапазоне параметров зависимость оптически индуцированного магнитного момента от температуры немонотонна и содержит максимум, обусловленный расфазировкой колебаний модуля и фазы параметра порядка при понижении температуры и соответствующем уменьшении характерного времени релаксации возмущений в сверхпроводящем конденсате.

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Switching between stable states of magnetization in SFS Josephson junctions on 3D topological insulator

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We demonstrated resonance effects in a system of nanomagnet coupled to the Josephson junction under the influence of external periodic drive. We show that the applied periodic drive brings to the appearance of additional resonance peaks, which positions determine by the driving frequency. The heights of the resonance peaks depend on the driving amplitude as a Bessel function. We develop a thorough analytical description that allows to classify all possible resonances arising in the system. The obtained result provide a method for controlling the resonance properties of the system. It has been demonstrated that by changing the amplitude of periodic drive it is possible to suppress the main ferromagnetic resonance and at the same time excite a new one with required amplitude and frequency. We consider that the obtained results open a wide field of research and applications related to the resonance properties of hybrid structures. Such a realization might play a crucial role in quantum information processing and spintronics.

Nonequilibrium phenomena in hybrid superconductor-ferromagnet structures

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Our recent investigations are related to superconducting spintronics in superconducting ferromagnet/superconductor (SF) structures. Fundamentally new structures and approaches for applications in superconducting electronics and spintronics are proposed. Among them Josephson SFS structures π-periodic current-phase relation [1], S-N/F-S devices with spin diffusion and spin injection [2], memory elements on the basis of SFS contacts [3]. We have repeated also well-known experiment by J.J.A. Baselmans et al [4] using the spin-polarized injection to Josephson barrier of SNS junction [5] (see Fig.1). We have observed two clearly distinct transitions: both from conventional (0-) to π-state (with inversion of superconducting phase difference) and back $\pi - 0$ transition. We suppose that the "Baselmans effect" mechanism related to energy electron redistribution is significantly complemented by influence of "induced magnetism" due to spin-diffusion [2].

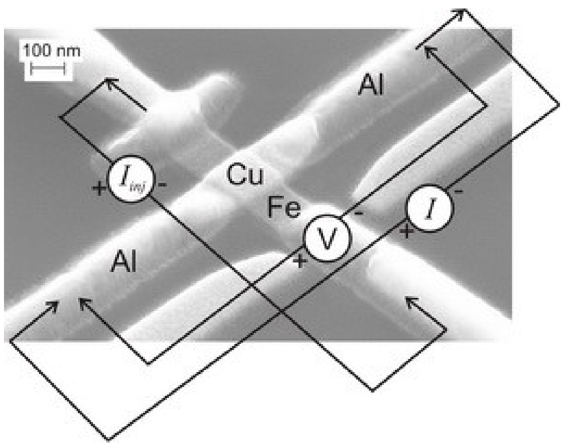

Figure 1: S-N/F-S structure with spin-injection.

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Magnetization reversal in a system of nanomagnet coupled to Josephson junction by cosine chirp pulse

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Next-generation computer applications demand a significant improvement in digital data processing with low energy consumption. One of the main obstacles to this goal is the trade-off between shortening the switching time and energy efficiency. We show that the magnetic switching of a nanomagnet driven by a circularly polarized cosine chirp microwave pulse demonstrates fast reversal with low field amplitude due to the coupling to the Josephson junction [1]. In this system, the magnetic state is stable against changes in pulse parameters. Also, we discuss controlling the magnetic state over the damping regime via the Josephson-to-magnetic energy ratio, which helps reduce the non-reversing magnetic response without further increase of the microwave field. Finally, we discuss the ability to reverse the magnetic state of the nanomagnet by Josephson currents in the form of a cosine chirp pulse. We believe that our results provide new perspectives on the reversal phenomenon in superconducting spintronic systems that might help realize fast memory devices.

The study is support by ASRT (Egypt) and JINR (Russia) collaboration research Projects. Numerical simulations were funded by Project No. 22-71-10022 of the Russian Science Foundation.

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Modeling of flux pinning mechanisms for tin-based inverted opals

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The present work is devoted to theoretical analysis of experimental data on the magnetization of tin superconductors with inverted opal structure. Two samples under considerations, named Sn190 and Sn300, were synthesized by filling with tin the porous in the SiO_2 opal matrices constructed from the spheres with diameter of 194 nm and 310 nm consequently. The obtained tin-based inverted opals are consisting from octahedral and tetrahedral particles connected by cylinders. The experimentally obtained magnetization reversal curves for the samples demonstrate some intriguing features. First, despite of the sample Sn300 is the type-I superconductor with critical field closed to thermodynamic one for bulk tin ($H_c \approx 305$ Oe), its magnetization reverse curve demonstrate irreversible behavior (hysteresis) in small fields ($|H| \ll Hc$). Second, the magnetization hysteresis loop for the Sn190 sample is similar to one for type-II superconductor and its upper critical field (H_{c2}) is much lager then H_c. Additionally, it is observed a local minimum at small fields on the reversal branche of hysteresis loop. To explain these features we suppose that the mechanisms of magnetic flux pinning in the samples under consideration depend on the sizes of the tin nanoparticles. The tin nanoparticles in Sn300 behave like a classical type-I superconductor. The hysteretic behavior at low magnetic fields is governed by Josephson junction network formed at the tin framework around the SiO_2 spheres. The magnetic behavior of Sn190 we supposed more complicated. The included tetrahedral tin particles with behave like type-II superconductors, and the included tin octahedra remain type-I superconductors. Thus, in Sn190, type-I and type-II superconductivities coexist, which leads to a nontrivial pinning of the magnetic flux. The transition of the flux pinning mechanisms is observed with the magnetic field increasing. At low fields the magnetic flux is trapped by ensemble of superconducting contours. At high fields the magnetic flux pinning works due to the surface barrier in the small tetrahedra tin particles. Based on such propositions we have performed the simulation of magnetic behavior of our samples. The calculation results we obtained are in the good agreement with experimental data.

Theoretical study of low coupled order parameters: Application to two-dimensional hybrid structures

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We theoretically study the proximity effect between non-conventional superconductors and ferromagnetic materials with and without an applied magnetic field and then provides a description of the properties of one-, two- and three-dimensional superconductor-ferromagnet heterostructures. Taking into account the intrinsic nature of structures composing the system, a particular attention is paid to the striking non-monotonic dependence of the critical temperature of multilayers and bilayers on the ferromagnetic layer thickness as well as to the conditions under which "Josephson junctions" are realized. Using the phenomenological Ginzburg-Landau theory (GLT) and the Eilenberger equation in the clean limit or the GLT and the Usadel equation in the dirty limit, it is demonstrated that the Josephson junction with such a ferromagnet as a weak link has a non-sinusoidal current-phase relation. The resulting coupled equations taking into account the geometry, the strongly fluctuating and correlated nature of low-dimensional system, are rather cumbersome for the 1D case but strongly simplified in the 2D or 3D case.

Neurobiological aspects in superconducting RSFQ-logic circuits

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Bio-inspired superconducting neuron, whose architecture is chosen so that its nature of functioning (generating SFQ spikes) resembles the work of a biological neuron, was investigated in different regimes or modes of functioning and each of these modes was given both a physical explanation and a biological analogy. The constructed areas of neuron parameters allowed us to identify the operating region in which, when the neuron's bias current changes, it is possible to switch between different modes of neuron operation. Furthermore, models of the axon (Josephson transmission line) and synapse (RLC-filter with additional Josephson junction) have been proposed. The synapse model developed allows us to demonstrate the effect of synaptic plasticity. Also, the work of a bundle of neuron+axon+synapse+axon+neuron was demonstrated.

Peculiar Physics of Heavy-Fermion Metals: Theory versus Experiment

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We considers the topological fermion condensation quantum phase transition (FCQPT) that leads to flat bands and allows the elucidation of the special behavior of heavy-fermion (HF) metals that is not exhibited by common metals described within the framework of the Landau Fermi liquid (LFL) theory. We bring together theoretical consideration within the framework of the fermion condensation theory based on the FCQPT with experimental data collected on HF metals. We show that very different HF metals demonstrate universal behavior induced by the FCQPT and demonstrate that Fermi systems near the FCQPT are controlled by the Fermi quasiparticles with the effective mass M strongly depending on temperature T, magnetic field B, pressure P, etc. Within the framework of our analysis, the experimental data regarding the thermodynamic, transport and relaxation properties of HF metal are naturally described. Based on the theory, we explain a number of experimental data and show that the considered HF metals exhibit peculiar properties such as: (1) the universal T/B scaling behavior; (2) the linear dependence of the resistivity on T, r(T) ~ A1T (with A1 being a temperature-independent coefficient), and the negative magnetoresistance; (3) asymmetrical dependence of the tunneling differential conductivity (resistivity) on the bias voltage; (4) in the case of a flat band, the superconducting critical temperature Tc ~ g, with g being the coupling constant, while the M becomes finite; (5) we show that the so called Planckian limit exhibited by HF metals with r(T) ~ T is defined by the presence of flat bands; (6) based on both, experimental facts and our theoretical consideration, we show that Fermi systems with flat bands should be tuned with the superconducting state. Experimental measurements on magic-angle twisted bilayer graphene of the Fermi velocity VF as a function of the temperature Tc of superconduction phase transition have revealed VF ∝ Tc ∝ 1/Ns(0), where Ns(0) is the density of states at the Fermi level. All our observations are in accordance with experimental facts.

Nonequilibrium superconductivity in nanowires InAs/Al

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We investigate semiconductor nanowires coated with an epitaxial superconducting shell, which are usually of interest in the context of the study of exotic states at the interface of a semiconductor and a superconductor [1-2]. In such problems, the state of the superconductor is not taken into account, and it is assumed that it is in an equilibrium state. In this paper, various manifestations of nonequilibrium superconductivity in transport measurements were found for several cases of contact between a macroscopic reservoir and a mesoscopic superconductor: superconductor-semiconductor, superconductor-normal metal, superconductor-superconductor.

We study InAs nanowires with a diameter of 170 nm with an epitaxial cylindrical Al shell with a thickness of 70 nm. We focus on two device layouts: Al contact pads were deposited on top of the nanowire (Type-I) and contact pads from normal metal were deposited on the nanowire, from the ends of which aluminum was previously etched away (Type-II). The differential resistance in magnetic field directed parallel to the nanowire at a temperature of 0.5 K demonstrates oscillations of the maximum position due to the Little-Parks effect [3]. Type-I has two operation modes: S-S-S in small fields and N-S-N in fields of large 10 mT, where Al contact pads have switched from superconducting to normal state. S-S-S behaves like an equilibrium superconductor, so in the zero field we find the value of the critical current of the Al shell equal to 0.35 mA. When switching to N-S-N, there is a sharp change in the volt-ampere characteristic. The nanowire acquires a finite resistance due to the NS-boundary; the superconducting shell cannot withstand a current half the critical one, and a critical voltage appears equal $V \sim \Delta(B)/e$. Numerical simulation of the order parameter versus the field using the Uzadel equation [4] coincides with the experiment, which makes it possible to explain the suppression of superconductivity as a nonequilibrium effect [5].

Comparison with the Type-II nanowire, where the Al shell was etched away to form an island 500 nm long, shows the qualitative effect of highly resistive semiconductor segments on superconductivity. In the zero field, superconductivity suppression occurs at a current of 0.3 mkA and a voltage of 2 mV. Note that for both layouts, current at which superconductivity is suppressed differs by orders of magnitude, and that superconductivity in the island is preserved at voltages much larger than the aluminum gap ($\Delta_{Al} = 0.18$ mV). We explain this effect by the fact that since the density of the above-gap states and the conductivity of the semiconductor segments are orders of magnitude less than in the island segment, nonequilibrium quasiparticles spend much more time in the island than the electron-phonon time, experiencing almost complete relaxation of energy. The measurement of shot noise in the absence of superconductivity in the 200 mT field gives the value of the Fano factor 0.2, which is less than the classical diffusion case 1/3 [6-7] and confirms the presence of strong electron-phonon relaxation in the island. The model calculation of the thermal balance is in acceptable agreement with the experiment.

Thus, we show that in studies of semiconductor nanowires with a superconductor, careful consideration of the effects of nonequilibrium superconductivity and energy relaxation on phonons is necessary.

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Dynamics and Resonance Phenomena in Anomalous Josephson Junctions

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I will present our recent results related to the study of SFS Josephson junctions with a shift in current-phase relation proportional to the magnetic moment of ferromagnetic layer. Such anomalous Josephson junctions (AJJ) combine the superconductivity and magnetism, and open up promising applications in superconducting spintronics [1]. Problems concerning a reversal of the magnetic moment by a superconducting current pulse, manifestation of Kapitsa pendulum features, the nonlinear properties and rich variety of periodic and chaotic behavior in the dynamics of the magnetic moment will discussed [2-4]. I will demonstrate a series of novel effects appearing in AJJ under external electromagnetic radiation [5,6].

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Fast two-qubit gates using transmon qubits with a tunable coupler

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Superconducting qubits is one of the most promising platforms for the implementation of quantum computing for today. The main problem on the way to constructing an efficient computational scheme is the limited fidelity of two-qubit gates. The architectural solution, which consists in the use of coupling elements between qubits [1], which allows to control the coupling strength of the qubits and even completely turn off the interaction, helps to solve some circuit scaling problems, such as frequency crowding, spurious couplings between qubits, and provides extremely fast two-qubit gates.

In this paper we present a two-qubit scheme on floating transmons with a tunable coupler. The qubit parameters are chosen in such a way as to minimize coherent leakage to non-computational energy levels while performing fast CZ and iSWAP gates. The developed scheme makes it possible to perform fast (~25 ns) two-qubit operations with an error of less than 1% even with rectangular control pulses, which significantly simplifies the calibration process.

The designed chip is fabricated on silicon substrates with aluminum Josephson junctions using bandage technology and superconducting air-bridge. As a result of experimental cryogenic measurements at temperatures below 20 mK, high coherence times (T1 > 100 µs, T2e > 100 µs) were demonstrated, High-fidelity single-qubit operations (F ~ 99.9%) and two-qubit fSim iSWAP-like gates (F ~ 99%) were implemented. These results are achieved through optimization of the qubit geometry and improved calibration techniques. The results of purity benchmarking [2] of single and two-qubits gates with low error are also presented, showing that the fidelity is mostly limited by coherent errors and could be further improved by additional calibrating procedures.

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Development of all-JJ logic circuits with Josephson 0- and π-junctions

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Quantizing magnetic flux in superconducting circuits enables fast and energy efficient digital superconducting circuits. However, it is a long-standing problem that the representation of information in magnetic flux severely limits the functional density. Here, we introduce the concept of fluxless and inductorless superconducting digital circuits. We present a methodology for designing different logic cells consisting of conventional and π Josephson junctions.

Properties of planar Josephson junction based on normal metal and magnetic insulator

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The presented work consists of two parts. The first describes a planar Josephson junction based on niobium and aluminum. The chosen process made it possible to achieve hysteresis-free behavior of such contacts. In combination with relatively large characteristic voltages $V_c = I_c R_n$ and small dimensions, such a contact can be used as part of RSFQ logic. Experimental results and theoretical description will be presented. In the second part, a Josephson junction fabricated on a Yttrium Iron Garnet substrate, which is a magnetic insulator, will be described. The results of experimental measurements and possible mechanisms of the influence of the substrate on the Josephson junction will be analyzed.

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Josephson vortex as a logical state of low dissipative devices

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Made of a thin non-superconducting metal (N) sandwiched by two superconductors (S), SNS Josephson junctions enable novel quantum functionalities by mixing up the intrinsic electronic properties of N with the superconducting correlations induced from S by proximity. Electronic properties of these devices are governed by Andreev quasiparticles which are absent in conventional SIS junctions whose insulating barrier (I) between the two S electrodes owns no electronic states. Here we focus on the Josephson vortex (JV) motion inside Nb-Cu-Nb proximity junctions subject to electric currents and magnetic fields. The results of local (magnetic force microscopy) and global (transport) experiments provided simultaneously are compared with our numerical model, revealing the existence of several distinct dynamic regimes of the JV motion. One of them, identified as a fast hysteretic entry/escape below the critical value of Josephson current, is analyzed and suggested for low-dissipative logic and memory elements. (RSF 23-72-30004)

Dynamical susceptibility of skyrmion crystal

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Magnetic skyrmions are topologically protected particle-like configurations of local magnetization, appearing particularly in non-centrosymmetric magnets with Dzyaloshinskii-Moriya interaction (DMI). It was observed that skyrmions are usually arranged into regular lattices both in bulk compounds and thin films, such lattices also called skyrmion crystals (SkX). Dynamics of SkX are complex and cannot be described in terms of displacements of skyrmion's centers only. There are a lot of inner modes associated with, e.g., elliptical deformation, clockwise rotation, counterclockwise rotation and breathing mode of skyrmions etc.

Using stereographic projection approach, we develop a theory for calculation of dynamical susceptibility tensor of SkX, formed in thin ferromagnetic films with DMI and in the external magnetic field [1]. Staying whenever possible within analytical framework, we employ the model anzats for static SkX configuration and discuss small fluctuations around it. The obtained formulas are numerically analyzed in the important case of uniform susceptibility, accessible in magnetic resonance (MR) experiments. We show that, in addition to three characteristic MR frequencies discussed earlier both theoretically and experimentally, one should also expect several resonances of smaller amplitude at somewhat higher frequencies.

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Finite momentum superconductivity in superconducting hybrids: Orbital mechanism

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Normally in superconductors, as in conductors, in the state with zero current I the momentum of superconducting electrons $\hbar q = 0$. Here we demonstrate theoretically and present experimental evidences that in superconducting/normal metal (SN) hybrid strip placed in the in-plane magnetic field B_{in} the finite momentum state ($\hbar q \neq 0$) is realized when $I = 0$. This state is characterized by current-momentum dependence $I(q) \neq -I(-q)$, nonreciprocal kinetic inductance $L_k(I) \neq L_k(-I)$ and different values of depairing currents $I^{\pm}_{dep}$ flowing along the SN strip in opposite directions. Found properties have *orbital* nature and are originated from gradient of density of superconducting electrons ∇n across the thickness of SN strip and field induced Meissner currents. We argue that this type of finite momentum state should be rather general phenomena in superconducting structures with artificial or intrinsic inhomogeneities.

Magnon influence on the superconducting DOS in S/F bilayers

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It is well known that the proximity effect in thin-film hybrid superconductor/ferromagnetic insulator structures provides the suppression of the superconductivity [1] and Zeeman splitting of the density of states in the superconductors [2]. In this poster we investigate the influence of ferromagnetic magnons on this effect. The density of states in the superconductor (DOS) and the quasiparticle spectra are calculated in the framework of Gor'kov Green's function approach. It is obtained that the interaction of superconducting electrons with magnons can result in a decrease of the Zeeman splitting of the DOS coherence peaks. It also inverts the ratio between the internal and external coherence peaks and smears the external peaks. The temperature dependence of the observed DOS characteristic features is investigated. It is demonstrated that quasiparticle spectra are also strongly modified by the electron-magnon interaction revealing characteristic kinks. The sensitivity of the results to the choice of materials and relevance to experiments are discussed.

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Resonance spin reversal in magnetic nanostructures

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There exist several nanostructures that are treated as convenient tools for producing memory devices and for using them in spin-based quantum computing. These, for instance, are magnetic nanomolecules, magnetic nanoclusters, magnetic graphene, polarized nanomaterials, quantum dots, and trapped dipolar and spinor atoms. The necessary requirement for such devices is the possibility of fast regulation of the spin direction. Methods for realizing fast spin reversal in these materials are described, based on the use of feedback field of a resonance electric circuit.

Towards the understanding of superconductors with quantum computations

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The emergence of digital quantum computers, which can efficiently perform quantum simulations that are otherwise intractable on classical computers, provides a promising path forward for testing and analyzing the remarkable, and often counter-intuitive, behavior of quantum materials.

In the beginning of the talk, recent developments in the field of quantum computing of complex electronic properties is briefly reviewed with the emphasis on the superconductivity (SC) and effects of strong electron correlations. As the first example, a simple quantum algorithm belonging to the class of Variational Quantum Eigensolvers (VQE) is discussed and applied for the mean-field description of SC order parameters with different spatial symmetries. Various VQE algorithms can in principle be implemented with the use of currently available quantum computers, referred to as noisy intermediate-scale quantum (NISQ) computers. Next, to study eigenstates and eigenvalues of a more general quadratic fermionic Hamiltonian with SC pairing interaction the famous Quantum Phase Estimation (QPE) algorithm can be applied, which, however requires a large-scale fault-tolerant quantum computer. Some further perspectives along this way will be discussed.

Study of superconductivity and magnetism in low-dimensional heterostructures by polarized neutron reflectometry

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Nowadays, the study of proximity effects at the interface between two media is in focus of research [1-5]. In particular, hybrid heterostructures, comprising superconducting (S) and ferromagnetic (F) layers are currently attracting great attention due to a diverse set of proximity effects. Manifestations of the influence of ferromagnetism on the superconducting properties of S/F heterostructures include phase changes of the superconducting wave function ("π-phase superconductivity") and spin-triplet Cooper pairing. Converse proximity effects in which superconductivity influences ferromagnetism have received less attention. These magnetic proximity effects (MPEs) are expected in systems where the F and S transition temperatures, T_F and T_C, are comparable, including for instance cuprate high-T_C superconductors and ferromagnetic manganates. Promising systems for study of MPEs are S/F heterostructures comprised of niobium and rare-earth (RE) materials. First of all high transparency of S/F interface is reported for such RE/Nb systems as Gd/Nb which simplifies penetration of superconducting correlations in F system [3,4]. Second, the REs are characterized by weak ferromagnetism, which equalize energies of both interactions and make MPEs easier. Last, but not least many REs such as Dy and Ho are known rare-earth ferromagnets with helimagnetic non-collinear structure, allowing for the generation of long-range triplet superconductivity. Taking into account all these considerations, RE/Nb structures are potentially interesting in the search of magnetic proximity effects.

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Information and computing system for spintronics tasks at JINR

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Nowadays, the main research activity in the field of nanotechnology is aimed at the creation, study and application of new materials and new structures. In the course of investigating the physics properties of these objects, it becomes necessary to numerically solve complex systems of nonlinear differential equations, which requires significant time and computational resources.

To date, algorithms and frameworks for modeling processes in various structures are actively developed. However, the functionality of existing packages does not allow one to fully implement the desired computation scheme.

To numerically solve the tasks of modeling hybrid nanostructures, it was decided to develop an information and computing system that provides a convenient set of tools for both developers and research groups. The use of the Python language simplified the process of writing a program to solve the tasks, while the use of specialized libraries made it possible to speed up computations. All stages of the research and the computations in the form of a Jupyter notebook are freely available on the resources of the HybriLIT heterogeneous platform using the Jupyter Book toolkit and are available to research groups via the link `http://studhub.jinr.ru:8080/books/`. In addition, they will be used for laboratory and research work by students and graduate students.

Anisotropic resistivity and superconducting instability in ferroelectric metals

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In our work we propose a theoretical model of a ferroelectric metal where spontaneous electric polarization coexists with the conducting electrons. In our model we adopt a scenario when conducting electrons interact with two soft transverse optical phonons, generalize it to the case when there is a spontaneous ferroelectric polarization in the system, and show that a linear coupling to the phonons emerges as a result. We find that this coupling results in anisotropic electric transport which has a transverse to the current voltage drop. Importantly, the obtained transverse component of the resistivity has a distinct linear dependence on temperature. Moreover, we show that the coupling enhances the superconducting transition temperature of the ferroelectric metal. We argue that our results help to explain recent experiments on ferroelectric strontium titanate as well as provide new experimental signatures to look for.

Спонтанные токи и генерация вихрей в гибридных структурах сверхпроводник/ферромагнетик с неоднородным обменным полем и эффектом Рашбы

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Существенное влияние на магнитные и транспортные свойства систем сверхпроводник(С) / ферромагнетик(Ф) оказывают спин-орбитальные (СО) эффекты, когда импульс электрона **p** оказывается связанным со спином σ. Исследование подобных гибридных систем представляет интерес как с точки зрения фундаментальной науки (поиск майорановских фермионов и топологической сверхпроводимости), так и из-за потенциальной применимости в интересах сверхпроводниковой спинтроники. Для широкого класса сверхпроводящих структур с планарной геометрией СО эффекты возникают из-за взаимодействия Рашбы $v_R[\mathbf{n}\times\mathbf{p}]\cdot\vec{\sigma}$, возникающего на интерфейсах таких структур [1]. Здесь **n** - это единичный вектор вдоль направления, в котором нарушена симметрия относительно пространственной инверсии, $\vec{\sigma}$ – вектор матриц Паули, а v_R - характерная скорость Рашбы, определяющая константу СО-связи $\alpha_R = \hbar v_R$. Хотя СО взаимодействие в сочетании с обменным полем **h** (или эффектом Зеемана) делает состояние с импульсом, направленным по $[\,\vec{\sigma}\times\mathbf{n}\,]$, более энергетически выгодным, в однородных системах это не приводит к генерации спонтанного сверхтока.

В докладе рассмотрены примеры тонкопленочных СФ структур с эффектом близости и СО взаимодействием Рашбы на интерфейсе, в которых обменное поле формирует в сверхпроводнике неоднородную магнитную текстуру [2]. Образование в сверхпроводнике спиральной фазовой модуляции только в ограниченной области сопровождается возникновением спонтанного сверхтока, амплитуда и распределение которого зависят как от силы СО взаимодействия, так и от структуры и величины обменного (зеемановского) поля. Изучены условия формирования в таких структурах вихревых состояний, индуцированных спонтанным током, и влияние магнитокиральных эффектов на джозефсоновский транспорт в планарных гибридных системах со слабыми связями.

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