Brief annotation

work cycle for the period 2017-2022,

nominated for the JINR Prize.

Title: The Anomalous Josephson Effect

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The Josephson effect, which consists in the tunneling of paired electrons through a barrier, finds enormous applications in various fields of science, technology, and medicine. In particular, devices based on it are used in superconducting electronics for measuring superweak magnetic fields, in quantum metrology as modern volt standards, and in medicine for recording magnetoencephalograms of the brain. The Josephson effect is the basis for generating and detecting coherent electromagnetic radiation in the terahertz region.

Until recently, it was not possible to combine superconductivity and magnetism, since these phenomena are antagonistic: a magnetic field destroys superconductivity, and superconductivity pushes out a magnetic field. However, in hybrid Josephson structures they have been brought close enough to allow superconductivity to control magnetism and magnetism to influence superconductivity [1]. Figuratively speaking, it became possible to "marry" them, and this "marriage" worked as a basis for a new field of science: superconducting spintronics. For this implementation, it was necessary to break two symmetries in the hybrid Josephson structure: the inversion symmetry and the time reversal symmetry. This leads to a change in the Josephson current-phase relation, where an addition to the phase difference of the wave functions of superconductors arises, which is proportional to the magnetization of the ferromagnet. Simultaneously with the change in the current-phase relation, an inverse effect of superconductivity on magnetism arises.

One of the main areas of our research is the solution of fundamental problems of superconducting spintronics - the development of fundamentally new methods for controlling the magnetization of magnets, as well as a radical reduction in energy consumption during the operation of spintronic devices.

The solution to the second problem was obtained in one of our first works [20], where a technique was developed and the reversal of the magnetic moment by a superconducting current pulse was demonstrated. Dissipationless control of magnetization makes it possible to significantly reduce energy consumption. At the next step, analytical criteria for reversal in structures of various types were found [7, 8], a periodicity in the occurrence of reversal intervals was found with a change in the parameters of the spin-orbit coupling and Gilbert damping, as well as the ratio of the Josephson energy to the magnetic one [15]. Well-known experts in the field of superconducting spintronics C. Guarcello and F.S. Bergeret used our flip method and proposed a cryogenic memory element based on an anomalous Josephson junction, Phys. Rev. Appl, 13, 034012, 2020.

Our further research was devoted to the development of fundamentally new methods for controlling magnetization. One of these methods was found in a detailed study of phase dynamics and current-voltage characteristics in structures with an anomalous Josephson effect. We have discovered a new effect - the manifestation of the properties of the Kapitsa pendulum (the appearance of dynamically stable positions of magnetization) in an anomalous Josephson junction [19, 20], as well as in the Josephson junction-nanomagnet system [4, 14], opening up the possibility of reorienting the easy axis of a ferromagnet. The uniqueness of this method lies in the fact that it allows you to change the orientation of the magnetization and the position of the points of stability due to the applied high-frequency periodic signal and opens up a new way to control the magnetization using a superconducting current.

We have also found a new method for controlling the dynamics of magnetic precession. The possibility of controlling the dynamics of magnetic precession with a superconducting current opens up wide scope for applications in superconducting electronics and spintronics. In our work [2], we demonstrated for the first time the indirect locking of the magnetic precession in the superconductor ferromagnet superconductor (S/F/S) junction by Josephson oscillations under the influence of an external periodic signal, which is reflected by the appearance of synchronization steps in the dependence of the magnetization on the current through the junction. The position of the step is determined by the radiation frequency and the shape of the resonance curve.

Another interesting effect is the manifestation of a state with a negative differential resistance (NDR) on the current–voltage characteristic of an anomalous Josephson junction. Such states can be used in switching circuits and multivibrator electronic devices. We have shown that in the region with NDR, an additional step appears on the current-voltage characteristic. Detailed studies [2] showed that the oscillations corresponding to this step have the same frequency as the oscillations on the first step, but they have a different amplitude. This makes it possible to control not only the frequency, but also the amplitude of the magnetic precession in the locking area. Unique prospects arise for the control and management of the magnetic moment dynamic in such hybrid systems.

We have obtained a number of other interesting effects manifested in hybrid nanostructures. In particular, it was demonstrated that new dynamically stable magnetization positions can lead to splitting of the easy axis of a ferromagnet in S/F/S Josephson junctions on the surface of a three-dimensional topological insulator [13]. It was shown that such a splitting leads to the stabilization of an unconventional fourfold degenerate ferromagnetic state. It was also shown that the voltage at the junction is related to the change in the magnetization component, which allowed us to propose a mechanism for electrical control of the magnetization in the S/F/S junction on the surface of a 3D topological insulator.

The most important characteristic of the Josephson structure measured experimentally is its current-voltage characteristic. In this regard, it has been studied in sufficient detail. For the first time, subharmonic staircase structures were found in the current–voltage characteristics, which are caused by the influence of the magnetization dynamics on the phase difference in the Josephson junction [10, 16–18]. Such structures can be used in various fields of superconducting spintronics. They are sensitive to changes in the periodicity in the dynamics of the system and can serve as an indicator of various exotic states. In particular, they can be used to detect Majorana bound states in Josephson nanostructures.

One of the most important tasks in the field of data coding and communication security is the development of methods for controlling and managing chaos. We have demonstrated a rich variety of periodic and chaotic behavior in the dynamics of the magnetic moment in the Josephson junction-nanomagnet (JJ-NM) system [3]. It was also shown that the chaotic behavior of the system can be controlled by applying an external periodic signal of the desired frequency and amplitude. It is assumed that such a system can be used as chaotic logic gates in computers based on chaotic systems.

Important results were obtained in the study of the resonance properties of hybrid nanostructures. In S/F/S structures [11, 12] and the JJ-NM system [15], we have demonstrated the shift of the resonant frequency caused by the interaction of the magnetic subsystem with the Josephson junction. The results obtained are of great practical importance. It is well known, that one of the methods for determining the characteristics of magnetic systems is ferromagnetic resonance (FMR). The standard FMR theory based on microwave absorption in magnetic materials shows that the resonant frequency is a function of the effective field, material and system parameters. This dependence can be used to determine the parameters of the material. On the other hand, these parameters can be varied to control the microwave absorption properties of the material. This two-way relationship between the FMR characteristics and the physical parameters of the system is usually based on analytical expressions that give the resonant frequency as a function of the material parameters (anisotropy constants, exchange and dipole couplings). In the case of hybrid structures, however, such analytical expressions cannot be obtained, and one has to resort to numerical simulation or some approximate solution. Our results provide the necessary information for estimating the physical parameters in S/F/S and JJ-NM hybrid structures.

Interesting results were obtained in the study of ferromagnetic resonance in hybrid structures of superconductors with a ferromagnet [1, 9]. A variety of regular dynamic states of magnetization along the current-voltage characteristic of the anomalous Josephson junction, characterized by specific phase trajectories, was demonstrated [12]. We have shown that they can be controlled, in particular, it has been demonstrated that external electromagnetic radiation makes it possible to fix a specific trajectory within the Shapiro step.

The nonlinear properties of hybrid structures are clearly manifested in the effect of the anomalous dependence of the resonant frequency on the Gilbert damping parameter, which was predicted by us [6]. This dependence was called the α-effect and was explained in [5, 6]. It has been demonstrated that the coupled system of Landau- Lifshitz -Gilbert-Josephson equations can be reduced to a scalar nonlinear Duffing equation. We have shown that there is a critical damping value at which cubic nonlinearity comes into play, changing the dependence of the resonance frequency on damping, leading to this dependence. A demonstration of the α-effect for various values of the spin-orbit interaction and the ratio of the Josephson energy to the magnetic one is given in our paper [5]. We have found a formula that predicts the critical damping value as a function of the spin-orbit coupling and the ratio of the Josephson energy to the magnetic one.

List of major publications

1. Шукринов Ю. М. Аномальный эффект Джозефсона, **УФН 192 345–385 (2022).**
2. S. A. Abdelmoneim, Yu. M. Shukrinov, K. V. Kulikov, H. ElSamman, and M. Nashaat. Locking of magnetization and Josephson oscillations at ferromagnetic resonance in a *φ0* junction under external radiation, **Phys. Rev. B 106, 014505 (2022).**
3. M. Nashaat, M. Sameh, A. E. Botha, K. V. Kulikov, Yu. M. Shukrinov. Bifurcation structure and chaos in nanomagnet coupled to Josephson junction, **Chaos 32, 093142 (2022).**
4. K. V. Kulikov, D. V. Anghel, A. T. Preda, M. Nashaat, M. Sameh, Yu. M. Shukrinov. Kapitsa pendulum effects in a Josephson junction coupled to a nanomagnet under external periodic drive, **Phys. Rev. B 105, 094421 (2022).**
5. A. Janalizadeh, I. R. Rahmonov, S. A. Abdelmoneim, Yu. M. Shukrinov and M. R. Kolahchi. Nonlinear features of the superconductor–ferromagnet–superconductor φ0 Josephson junction in the ferromagnetic resonance region, **Beilstein J. Nanotechnology 13, 1155–1166 (2022)**
6. Yu. M. Shukrinov, I. R. Rahmonov, A. Janalizadeh, and M. R. Kolahchi. Anomalous Gilbert damping and Duffing features of the superconductor-ferromagnet-superconductor φ_0 Josephson junction, **Phys. Rev. B 104, 224511 (2021).**
7. I. V. Bobkova , A. M. Bobkov, I. R. Rahmonov, A. A. Mazanik , K. Sengupta, and Yu. M. Shukrinov. Magnetization reversal in superconductor/insulating ferromagnet/ superconductor Josephson junctions on a three-dimensional topological insulator**, Phys. Rev. B 102, 134505 (2020).**
8. A. A. Mazanik, I.R. Rahmonov, A.E. Botha, and Yu. M. Shukrinov, Analytical criteria for magnetization reversal in a φ_0 Josephson junction, **Phys. Rev. Applied 14, 014003 (2020).**
9. Yu. M. Shukrinov, I. R. Rahmonov, and A. E. Botha. Peculiarities of IV characteristics and magnetization dynamics in the φ0 Josephson junction, **Low Temp. Phys. 46, 932 (2020).**
10. M. Nashaat and Yu. M. Shukrinov, Ferromagnetic resonance and effect of supercurrent on the magnetization dynamics in S/F/S junctions under circularly polarized magnetic field, **Phys. Part. Nuclei. 17 (1), 7984 (2020).**
11. Y.M. Shukrinov, and I.R. Rahmonov, Resonance Properties of the Josephson Junctions with Ferromagnets, **Phys. Part. Nuclei. 51, 816822 (2020).**
12. Yu. M. Shukrinov, I. R. Rahmonov, and K. Sengupta, Ferromagnetic resonance and magnetic precessions in Phi-0 junctions, **Phys. Rev. B 99, 224513 (2019).**
13. M. Nashaat, I. V. Bobkova, A. M. Bobkov, Yu. M. Shukrinov, I. R. Rahmonov, and K. Sengupta. Electrical control of magnetization in superconductor/ ferromagnet/ superconductor junctions on a three-dimensional topological insulator, **Phys. Rev. B 100, 054506 (2019).**
14. Yu. M. Shukrinov, M. Nashaat, I. R. Rahmonov, and K. V. Kulikov, Ferromagnetic resonance and the dynamics of the magnetic moment in a Josephson junction– nanomagnet system, **JETP Letters 110 (3), 160–165 (2019).**
15. П. Х. Атанасова, С. А. Панайотова, И. Р. Рахмонов, Ю. М. Шукринов, Е. В. Земляная, М. В. Башашин. Periodicity in the Appearance of Intervals of the Reversal of the Magnetic Moment of a ϕ0 Josephson Junction, **Письма в ЖЭТФ, 110, 736 (2019).**
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17. Yu. M. Shukrinov, I. R. Rahmonov, and A. E. Botha. Superconducting Spintronics in the presence of spin-orbital coupling, **IEEE Transactions on Applied Superconductivity, 28 (7), 1800505 (2018).**
18. M. Nashaat, A. E. Botha, and Yu. M. Shukrinov. Devil's staircases in the IV characteristics of SFS Josephson junctions, **Phys. Rev. B 97, 224514 (2018).**
19. Yu. M. Shukrinov, A. Mazanik, I. R. Rahmonov, A. E. Botha and A. Buzdin. Re-orientation of easy axis in φ_0 junction, **EPL. 122, 370012 (2018).**

20. Yu. M. Shukrinov, I. R. Rahmonov, K. Sengupta, and A. Buzdin, Magnetization reversal by superconducting current in Josephson junctions, **Appl. Phys. Lett. 110, 182407 (2017).**