Superconducting and mesoscopic structures

(Preface)

It is remarkable, that for 40 years the Josephson effect maintains its position in the centre of condensed matter physics. The reason is, probably, in the very concept of weak coherent coupling between macroscopic quantum systems. It allows to separate the effects of interaction, which creates the long-range order, from the correlation themselves, corresponding to this order. It provided the possibility to investigate the overlap of mutually exclusive (in the bulk) long-range orders. It gives the opportunity to look at the effects of finite size of the system. Josephson effect also gives the framework for discussing and realization of macroscopic quantum phenomena (beyond the almost trivial fact that superconductors are macroscopic quantum objects). Last five years saw the demonstration of macroscopic quantum resonant tunneling, quantum coherence and quantum entanglement in Josephson structures. Josephson physics repaid the physics of bulk superconductivity by providing means of investigations of unusual superconductors (e.g., demonstrating d-wave symmetry in high-T_c cuprates).

Brian D. Josephson discovered his remarkable effect in 1962. Josephson predicted that a zero voltage supercurrent could flow in a junction between two superconductors separated by a tunnel barrier. The magnitude of the Josephson current is related to the difference of the phases of the macroscopic wave functions (complex order parameters) of superconductors forming the junction. P.W. Anderson and J.M. Rowell first observed this dc Josephson effect in 1963. If a dc voltage V is applied to the junction, ac supercurrent with the frequency $2eV/\hbar$ appears between the superconductors. The first direct observation of the ac Josephson effect was done 40 years ago in Kharkov (I.K. Yanson, V.M. Svistunov, and I.M. Dmitrenko, *Zh. Exp. Teor. Fiz.* **47**, 2091 (1964); *ibid.* **48**, 976 (1965)). Soon after Josephson's predictions for the tunnel junctions, it became clear that the effects are much more general and occur whenever two superconductors are weakly coupled. The physics of weak superconductivity (term introduced by P.W. Anderson) became an area of a great interest for experimental and theoretical investigations. More than forty years after its discovery, the Josephson effect still attracts considerable attention and keeps providing us with new exciting physics and applications.

This issue is devoted to aspects of the physics of superconducting and mesoscopic structures. It presents reviews and original articles on the subject. The papers by Yanson and Dmitrenko, which are opening of the issue, review the initial steps in study of the ac Josephson effect in tunnel junctions and further experimental investigation of weakly coupled superconductors at Kharkov's Institute for Low Temperature Physics and Engineering.

The Josephson effect arises in superconducting weak links — junctions of two weakly coupled superconductors (massive banks) S_1 and S_2. The coupling allows the exchange by electrons between the banks and establishes the superconducting phase coherence in the system as a whole. The weakness of the coupling means that the superconducting order parameters of the banks are essentially the same as for disconnected superconductors, and they are characterized by the phases of the order parameters χ_1 and χ_2. The Josephson weak link can be considered as a «mixer» of the two superconducting macroscopic quantum states in the banks. The result of the mixing is a phase dependent current carrying state with current flowing from one bank to another. This current is determined (parameterized) by the phase difference $\varphi = \chi_2 - \chi_1$ across weak link. The specific form of the current–phase relation $I(\varphi)$ depends on the type of the weak link.

A number of papers consider the coherent transport in Josephson weak links with coupling more complicated then the just tunneling barrier. In the paper by Kulik different types of superconducting weak links are reviewed, focusing on the origin of jumps in current–phase dependencies. The author discusses as well persistent currents in the mesoscopic and nanoscopic Aharonov–Bohm structures. Novel effects in superconducting nanojunctions are studied theoretically in the paper by Zaikin. It is shown, that interplay between quantum interference effects and Andreev reflection in S–N–S junctions with insulating barriers may qualitatively modify the Josephson current. Several papers included deal with spin effects in mesoscopic Josephson junctions. Shnirman et al. study the dynamics of a single spin embedded in the tunneling barrier between two superconductors. New effect of the «Josephson nutation» is predicted. The paper by Krive et al. reviews the charge and spin effects in S–Luttinger liquid–S and S–quantum wire–S junctions.

The properties of the current carrying states in a weak link depend not only on the coupling manner but also on the properties of the superconducting banks. The modern physics of superconductivity is essentially the physics of unconventional superconductivity. The discovery of d-wave symmetry of the order parameter in high-temperature superconductors and of triplet superconductivity in compound Sr_2RuO_4 has caused a stream of theoretical and experimental research of unconventional superconductors. The sensitivity of Josephson effect to the symmetry of the complex order parameter in the junction's banks stimulated numerous studies of Josephson weak links between unconventional superconductors. The current–phase relations for unconventional Josephson weak links are quite different from the conventional ones. For example, in grain boundary junctions, depending on the angle of miss-orientation of d-wave order parameters in the banks, the current–phase relation is changed from $\sin(\varphi)$ like curve to $-\sin(2\varphi)$ dependence. Clearly, it determines new features in behavior of such Josephson junctions in applied voltage or magnetic field. Considerable number of papers included concerns the study of unconventional Josephson weak links. One of the most striking manifestations of the unconventional order parameter symmetry is the appearance, together with the Josephson current, of the spontaneous current flowing along the contact interface. The spontaneous current arises due to the breaking of the time-reversal symmetry (T) in the system. The study of T-breaking phenomena is not only of a fundamental significance but also attracts interest from the point of realization of qubits, basic units of quantum computers. The review by Kolesnichenko et al. focuses on spontaneous currents in junctions between d-wave and triplet superconductors. It also contains the review of superconducting qubits basics with emphasizing on the properties of d-wave qubits. A theoretical paper by Tanaka et al. considers the impurity scattering effect on charge transport in high-T_c cuprate junctions. The results of experimental investigations of high-T_c grain boundary junctions and heterostructures are presented in the papers by Tafuri et al., Komissinski et al. and Timofeev et al. The specific features of ac Josephson effect in unconventional superconductors are reported in the theoretical paper by Kwon et al. Note that the problem of existence of fractional ac Josephson effect in unconventional superconductors needs further theoretical and experimental investigations.

Mesoscopic structures, consisting of several Josephson junctions, are studied now intensively from the point of view of qubit realization. A paper by Il'ichev et al. summarizes the results of implementation of the advanced impedance measurements technique for characterization of interferometer-type superconducting qubits. In a theoretical paper by Ioffe et al. a new class of Josephson arrays is introduced. These arrays have nontrivial topology and exhibit novel quantum states at low temperatures. In the paper by Kuplevakhky, the detail theory of Josephson vortices in layered superconductors is developed. The quantum dynamics of order parameter and time dependent BCS pairing in the frame of Wigner distribution function is investigated by Amin et al.

A single issue cannot cover all aspects of the research. It gives the reader a brief overview of the current state of activities, which, we hope, will be useful and will stimulate further investigations in the field of superconducting and mesoscopic structures.

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