Superconductivity is for over a century one of the most fascinating phenomena, in which the quantum character of matter manifests itself on a macrosopic scale by the perfect conductance (loss of resistance) and perfect diamagnetism (Meissner effect). Its underlying mechanism is related to the electron pairing that can be of various origins. Such pairing mixes the particles (occupied states) and holes (empty states) with each other, leading to a breakdown of the Fermi-liquid picture. The recent technological development opens novel possibilities to achieve the superconductivity in ultra-small objects such as atoms, molecules, carbon nanotubes, nanowires and in other systems of the spatially limited regions. The effective electron pairing can be spread onto such objects via the proximity effect, i.e. by attaching them to the bulk superconductors.

When confronting the proximity-induced pairing with the Coulomb repulsion and/or other types of interactions (like the spin-orbit coupling or influence of the magnetic field) one can observe very exotic phenomena, completely unknown in the bulk systems. For instance, one can realize (in experimentally tunable way) a qualitative changeover of the ground state, so called, quantum phase transition. In circuits consisting of two bulk superconductors with the correlated nanoscopic island embedded between them, this transition is evidenced by a reversal of the d.c. Josephson current. In other tunneling configurations, comprising conducting and superconducting electrodes, such transition [or crossover] is manifested by a crossing of the quasiparticle energies and can eventually imply constructive influence of the electron pairing on the many-body Kondo effect (whereas in the bulk materials the electron pairing and magnetic order are know to be foes to each other). In more complex multi-terminal junctions there can be also observed other intriguing phenomena, caused by nonlocal scattering processes due to the crossed Andreev reflections. They can give rise to the negative charge conductance or unique thermoelectric features, none of them feasible in the bulk materials. All aforementioned effects can be assigned to the bound (Andreev or Yu-Shiba-Rusinov) states of these nanosystems appearing inside the energy gap of superconducting reservoir.

During the recent few years there has been enormous (theoretical and experimental) activity in studying the exotic phenomena of the nanoscopic topological superconductors. Such superconductivity (characterized by topological invariants) has been indeed observed in the proximitized nanowires, revealing the Majorana-type features in the low energy spectrum. Such exotic particles (identical with their antiparticles) emerge near the ends of the finite-length nanowires appearing at the zero energy, where by `zero' we mean the chemical potential (which is the border-line between particles and holes). The zero-energy Majorana quasiparticles are topologically protected (i.e. any local perturbation cannot destroy them), therefore they are immune to decoherence. Furthermore, they obey non-Abelian statistics so would be perfect candidates for the quantum bits (qubits) and might enable the fault-tolerant quantum computing. Formally the Majorana modes can be regarded as mutations of the Andreev/Shiba quasiparticle states which are present under specific conditions.

In this project will investigate these and related phenomena uniquely appearing in the finite-size superconductors in low dimensions. Our studies would be carried out in a collaboration with the scientists from Poland and abroad. Such topics are important for the basic science and might be instructive for designing brand new devices of nanoelectronics.