Scientific hypothesis and the research objectives

Recent intensive theoretical and experimental activities focus on studying the unique phenomena of the novel materials and nanostructures, in which the proximity-induced superconducting state reveals *inter alia* some topological and quantum properties without analogy to any bulk system. Technological development opened possibilities to achieve and probe such exotic superconductivity e.g. in atoms, molecules, carbon nanotubes, nanowires and other ultra-small objects. Under specific conditions one can obtain the topologically nontrivial superconducting phase whose spectacular signatures reveal the Majorana-type quasiparticles in the low energy spectrum. They have been indeed observed experimentally in the proximitized magnetic nanowires/nanochains, in lithographically produced structures and in the vortices of *p*-wave superconductors. Zero-energy Majorana quasiparticles (identical to their antiparticles) are topologically protected, i.e. any local perturtbation cannot destroy them. They are immune to decoherence and obey the non-Abelian (anyon) statistics, so they would be perfect candidates for qubits (quantum bits) and might enable the fault-tolerant quantum computing. Formally these Majorana modes can be regarded as mutations of the Andreev/Shiba quasiparticle states - these quasiparticles are the main subject of this research project. In particular, we are going to investigate:

- (i) role of the bound in-gap states in multiterminal structures, focusing on the non-local charge, spin and energy transport properties,
- (i) dynamical effects (quantum quench, transient phenomena, shot-noise, waiting time distribution),
- (ii) quantum phase transitions due to the subtle interplay betwee electron pairing and correlations, and analysis of their feasible observability controlled by the electrostatic/magnetic means,
- (iii) investigation of the spin-polarized Majorana quasiparticles in the topological superconductors,
- (iv) charge/spin teleportation driven by the crossed Andreev scattering via the Majorana quasiparticles,
- (v) role of the spin-orbit interactions in nanoscopic superconductors.

Methodology of the research project

To account for the electron pairing and correlation effects in nanoscopic systems we will use several methods, like: (i) selfconsistent perturbative treatment of the Coulomb potential, (ii) exact solution for large superconducting gap and its recent extensions, (iii) perturbative treatment of the coupling to both external reservoirs, (iv) continuous-time Quantum Monte Carlo simulations and (v) Numerical Renormalisation Group technique calculations. For studying the Majorana quasiparticles we will investigate the topological superconducting state in finite-length quantum wires by the Bogolubov de Gennes approach or using some effective models. This method gives insight into the spatially and spin dependent phenomena and other effects due to internal quantum defects, interfaces or inhomogeneities. Dynamical effects for the bound states will be addressed by (i) solving the Heisenberg equation of motion for the second quantization operators, (ii) determining time-dependence of the evolution operator, (iii) computing non-equilibrium Green's function along the Keldysh contour or (iv) other methods, like the full counting statistics, the waiting time distribution approach, etc.

Expected impact of the project on development of science and society

Studies of the nonlocal processes, nonequilibrium thermodynamics, quantum phase transitions, Majorana quasiparticles, spin-selective crossed Andreev scattering, electron teleportation, and the spatially- or time-resolved spectroscopies. Intensive studies of these issues would be valuable for the basic science. There are good reasons to expect that at least some of these effects could find practical use in quantum information (qubits, quantum computation), novel electronic and spintronic devices, sensitive detectors of magnetic field (important for medical applications) or other nanotechnological applications. Most of the tasks proposed in this project will be done in collaboration with the renowned experts from Poland and abroad. Such initiative could be especially beneficial for the younger members (Ph.D. students engaged in realization of this grant) and would strengthen cooperation of the M. Curie-Skłodowska University with the European research institutes.