Abstract of doctoral dissertation

Influence of spin-orbit interactions on bound states in superconductors

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Bound states in superconductors induced by classical magnetic impurities were first considered in the late sixties. A recent revival of interest in this topic stems from the proposals of obtaining topological phases via the interaction of a Yu-Shiba-Rusinov band, coming from a cluster of impurities, with the superconducting host with spin-orbit coupling.

In the present thesis, various effects of interaction between the spin-orbit coupling and Yu-Shiba-Rusinov states were analyzed. It has been shown that in a triangular lattice, this interaction can increase the spatial extent of bound states and influence the impurity coupling responsible for the quantum phase transition – a generic feature of Shiba states.

A different type of the spin-orbit interaction, introduced as a necessary ingredient for the quantum spin Hall effect in honeycomb lattices, turned out to have a detrimental effect on the spatial extent of the wave function of the bound state. Additionally it greatly increases the critical magnetic coupling of the impurity and modifies the reversal of the current induced by the impurity, by introducing an additional pair of bound states in the gap.

Topological phases require the presence of a Shiba band, hence more than one impurity is needed. A cluster of classical magnetic impurities, with their moments aligned ferromagneticaly in the plane of the superconducting host has been analyzed. With the Ising spin-orbit coupling, characteristic for transition metal dichalcogenides, this system is a nodal topological superconductor. Between the nodes – special points in momentum space, where the superconducting gap closes – flat Majorana bands appear. This leads to localized, zero-energy Majorana states on the edge of the sytem. These are quasiparticles which are their own antiparticles and are proposed to be the perfect candidates for topological qubits.

If the magnetic moments of impurities comprising the Shiba island are aligned perpendicular to the plane of the superconducting surface, Rashba spin-orbit coupling drives the system into a chiral superconducting state, with Cooper pairs having non-zero angular momentum. It has been shown that coupling of two van der Waals materials – $CrBr_3$ and $NbSe_2$ leads to emergence of a topological superconducting state with Chern number $C = 3$. This exotic phase is manifested by the presence of a one dimensional, chiral Majorana mode on the edge of the impurity island

Josephson junctions with a spin-orbit coupled semiconductor serving as the tunneling barrier, can be controlled by a phase difference and tuned into a topologically non-trivial phase. This leads to Majorana states emerging at the ends of the barrier region, similarly to those found in topological nanowires. It has been presented that the presence of non-trivial edge states can be probed by Majorana polarization – a complex version of the local density of states. It has been also shown that its absolute value is proportional to the spin selective Andrev current. Additionally a tendency towards localization of the Majorana state around a scalar impurity has been presented.

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