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Topological properties of Josephson current between two s- and p-wave superconducting nanowires with Majorana fermions

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Josephson current between two one-dimensional nanowires with proximity induced either s-wave or p-wave pairing and separated by a narrow dielectric barrier is calculated in the presence of Rashba spin-orbit interaction (RSOI), in-plane and normal Zeeman magnetic fields (ZMF). A topological superconducting phase in a Josephson junction of s-wave superconductors (s-JJ) is realized under the condition $|\ |^2 > B^2 + h^2$, where Δ, B, and h are correspondingly the gap, Zeeman energy of in-plane and normal magnetic fields. Instead, the condition $_k = \frac{\vec{k}}{|k|}\ _0$ guarantees an existence of a conducting state in the gap and realization of a generic topological phase of the p-wave superconductor (p-JJ). Andreev retro-reflection is shown to be realized through two different channels. A scattering in a conventional particle-hole channel, when an electron-like quasi-particle reflects to a hole-like quasi-particle with opposite spins, provides the current which depends only on the order parameters' phase differences ϕ, and oscillates fractionally with 4π period. Fractional oscillation of the current with 4π period is the main manifestation of realization of Majorana fermion in the system. Second anomalous particle-hole channel, corresponding to the Andreev reflection of an incident electron-like quasi-particle to hole-like quasiparticle with the same spin orientation, survives only in the presence of the in-plane magnetic field. The contribution of this channel to the Josephson current oscillates with 4π period not only with ϕ but also with orientational angle of the in-plane magnetic field θ resulting in a magneto-Josephson effect. RSOI and ZMF are shown to split the quasi-electron and quasi-hole excitation states in the superconducting gap, and two quasi-particle and quasi-hole pairs instead of one pair appear in the gap, which are localized symmetrically around Fermi level. ZMF is shown to destroy this symmetry. Even in the absence of the magnetic fields in s-JJ the energy gap between the Andreev bound states decreases with increasing RSOI. Investigation of ac-Josephson current in s-JJ shows that the width of the resulting Shapiro steps in such a system can be tuned by varying the RSOI constant. In the presence of RSOC and normal-to-plane magnetic field h in p-JJ, a forbidden gap is shown to open in the dependence of Andreev bound state energies on the phases ϕ and θ at several values of RSOC strength and ZMF, where Josephson current seems to vanish [1].

References:

[1] E. Nakhmedov, B. D. Suleymanli et al., submitted to Phys. Rev. B (ArXiv: 1911.09289).

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