Odd-frequency pairing state in superconducting junctions

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We have clarified the ubiquitous presence of odd-frequency pairing states in non-uniform superconductor junctions. This means that the odd-frequency pairing is not at all a rare situation as was previously assumed. Here, we present recent results about odd-frequency pairing state.

(1) Theory of the proximity effect in junctions with unconventional superconductors [1]

We present a general theory of the proximity effect in junctions between diffusive normal metals (DN) and unconventional superconductors in the framework of the quasiclassical Green's function formalism. Various possible symmetry classes in a superconductor are considered which are consistent with the Pauli principle: even-frequency spin-singlet even-parity (ESE) state, even-frequency spin-triplet odd-parity (ETO) state, odd-frequency spin-triplet even-parity (OTE) state and odd-frequency spin-singlet odd-parity (OSO) state. It is shown that the pair amplitude in a DN belongs respectively to an ESE, OTE, OTE and ESE. The generation of the OTE state in the DN attached to the ETO p-wave superconductor is of particular interest in the relevance to the novel proximity effect in Sr_2RuO_4 junctions.

(2) Anomalous Josephson Effect between Even- and Odd-Frequency superconductors [2]

We also studied about the ballistic normal metal / superconductor junctions based on the standard quasiclassical Green's function theory. We demonstrate that, quite generally, the spin-singlet even-parity (spin-triplet odd-parity) pair potential in a superconductor induces the odd-frequency pairing component with spin-singlet odd-parity (spin-triplet even-parity) near interfaces. The magnitude of the induced odd-frequency component is enhanced in the presence of the midgap Andreev resonant state due to the sign change of the anisotropic pair potential at the interface. We demonstrate that, contrary to standard wisdom, the lowest-order Josephson coupling is possible between odd- and even-frequency superconductors. The origin of this effect is the induced odd(even)-frequency pairing component at the interface of bulk even(odd)-frequency superconductors. The resulting current phase-relation is found to be proportional to $\cos\phi$, where ϕ is the macroscopic phase difference between two superconductors.

The underlying physics behind this phenomena can be explained as follows. Near the interface, due to the breakdown of translational invariance, the pair potential acquires a spatial dependence which leads to the coupling between the even and odd-parity pairing states. The Fermi-Dirac statistics then dictates that the induced pair amplitude at the interface should be odd (even) in frequency where the bulk pair potential has an even (odd)-frequency component. Consequently, the Josephson coupling between even and odd-frequency superconductors becomes possible. To be compatible with the time reversal invariance in each superconductor, the phase of the interface induced pair amplitude undergoes a $\pi/2$ shift from that of the bulk one. This twist of the phase of the pair amplitude gives rise to an anomalous Josephson current, where the current phase relation is proportional to $\cos\phi$.

[1] Y. Tanaka and A.A. Golubov, Phys. Rev. Lett. **98** 037003 (2007).
[2] Y. Tanaka, A.A. Golubov, S. Kashiwaya and M. Ueda, condmat0610017, to be published in Phys. Rev. Lett.