

Large spectral gap and impurity-induced states in a two-dimensional Abrikosov vortex

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We study the subgap quasiparticle spectrum of a 2D Abrikosov vortex in an s-wave superconductor in the absence and presence of a magnetic or nonmagnetic point impurity [1]. Within the Eilenberger equations formalism, we calculate the energy spectrum of a vortex within two models: a "coreless" vortex with a constant modulus of the order parameter, and a more realistic vortex with the order parameter profile satisfying the Ginzburg-Landau equation. Both models yield qualitatively similar results. For a vortex without impurity, in addition to the known anomalous spectral branch, we find multiple upper branches corresponding to localized Andreev states. The number of these branches can be arbitrarily large provided that the magnetic field screening length is large enough. The large number of branches appears because of the Doppler effect connected with spontaneous currents in the vortex. These currents lower the effective gap edge, creating a potential well that is large enough to accommodate many Andreev states with the same angular momentum.

The quasiclassical local density of states in the vortex has a gap (more precisely, a double-gap symmetric with respect to the Fermi energy) with a width of the order of the bulk gap and a spatial extent of several coherence lengths. The existence of such a gap is the prerequisite for the appearance of discrete impurity-induced states. Indeed, within the Gor'kov equations formalism, we find that a single impurity induces up to four discrete quasiparticle states in the vortex. The energies and wave functions of the impurity states are calculated for different parameters. In a sense, our study extends the analysis of impurity-induced states by Larkin, Ovchinnikov and Koulakov [2] from the limit of low energies to the whole subgap energy range. Most of the spectral features that we have found can be observed in scanning tunnel microscopy/spectroscopy experiments.

[1] A. A. Beshpalov and V. D. Plastovets, *Phys. Rev. B* 103, 024510 (2021).

[2] A. I. Larkin and Yu. N. Ovchinnikov, *Phys. Rev. B* 57, 5457 (1998); A. A. Koulakov and A. I. Larkin, *Phys. Rev. B* 59, 12021 (1999); A. A. Koulakov and A. I. Larkin, *Phys. Rev. B* 60, 14597 (1999).