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Spontaneous time-reversal symmetry breaking due to emergence of new order along [110] surfaces of nanoscale d-wave systems

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Time-reversal symmetry (TRS) and topological phenomena associated with it are hot topics in condensed matter physics. The existence of the gapless Andreev bound states on [110] surfaces of a high-Tc cuprate superconductor is guaranteed by the bulk-edge correspondence to a topological invariant protected by TRS. Recent experiment on a nanoscale cuprate island
has detected a full gap that is consistent with broken TRS [1]. By solving the Bogoliubov-de Gennes equations self-consistently for d-wave nanoislands and nanoribbons with [110] surfaces, we show that TRS is spontaneously broken at low temperatures with spontaneous emergence of a new complex order parameter along the [110] surfaces. This new order parameter has extended s-wave symmetry and its magnitude determines the splitting of the Andreev bound states, which are gapped due to the loss of topological protection by TRS. We find this phase transition within the TRS-preserved d-wave phase to be of second order and a generic feature of [110] surfaces. Furthermore, when the side length of a nanoisland or the width of a nanoribbon is relatively large, vortex-antivortex pairs appear along the surfaces, each of which contains Andreev bound states. The TRS-broken phase, with or without vortex-antivortex pairs, can be distinguished from the TRS-preserved phase by means of surface-sensitive probes [2].

[1] D. Gustafsson *et al.*, Nat. Nano. **8**, 25 (2013).

[2] Y. Nagai, Y. Ota, and K. Tanaka, arXiv :1610.05501.

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