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Persistently negative: nonlocal Andreev reflection in a chiral mode

1. **Evidence for chiral supercurrent in quantum Hall Josephson junctions**
   Authors: Hadrien Vignaud, David Perconte, Wenmin Yang, Bilal Kousar, Edouard Wagner, Frédéric Gay, Kenji Watanabe, Takashi Taniguchi, Hervé Courtois, Zheng Han, Hermann Sellier, Benjamin Sacépé
   arXiv:2305.01766

2. **Induced superconducting correlations in the quantum anomalous Hall insulator**
   Authors: Anjana Uday, Gertjan Lippertz, Kristof Moors, Henry F. Legg, Andrea Bliesener, Lino M. C. Pereira, A. A. Taskin, Yoichi Ando
   arXiv:2307.08578

Recommended with a Commentary by Anton Akhmerov, Kavli Institute of Nanoscience, Delft University of Technology

The quest for combining superconductivity and the quantum Hall effect is several decades old. The conceptual idea is simple and powerful: a chiral edge mode is a one-way street. Therefore, when an electron reflects from an edge state into a superconductor, the resulting particle—no matter whether electron or hole—propagates in the same direction as the incoming electron. This way, the spatial separation between electrons and holes is maximal and the local reflection is fully prohibited. If the probability for the hole to exit the superconductor is larger, a positive voltage between the injecting electrode and the superconductor results in a negative current between the superconductor and the collecting electrode, providing a straightforward signature of nonlocal Andreev reflection.

A related phenomenon, *quantum Hall supercurrent*, appears when two superconducting electrodes are connected by a quantum Hall edge. Its hallmark is the periodicity of the supercurrent with the number of normal (h/e) and not superconducting ($h/2e$) flux quanta of magnetic field through the junction area. The change in periodicity compared to the regular Fraunhofer pattern in Josephson junctions also arises due to the chiral nature of the edge mode: all quasiparticles carrying supercurrent must encircle the complete sample. Just like Andreev reflection, quantum Hall supercurrent is a nonlocal phenomenon that requires coherent transport of quasiparticles in contact with a superconducting electrode. Both are therefore suppressed by superconducting vortices that act like quasiparticle sinks and by dephasing due to inelastic scattering.

The early progress in the field was impeded predominantly by material issues. In the last several years, the advances in 2D materials, most notably graphene, enabled a series of successful experimental works. The state of the art from December 2021 was reviewed by the community in an online workshop [1] that I have co-organized together with colleagues. I invite interested readers to read the workshop summary and watch the recordings, while here I will only highlight the relevant outcomes of the discussion. Firstly, some experiments observe a systematically negative nonlocal conductance [2, 3], whereas other works see mesoscopic conductance fluctuations with zero average [4]. The latter is a natural result of an interplay between multiple Andreev reflections and disorder, and is therefore expected [5, 6]. To the best of my knowledge, the former lacks microscopic theory so far, and remains a puzzle. The supercurrent signature remained unobserved at that time, with the experiments dominated by local Andreev reflection into additional non-chiral modes present at a graphene edge [7].

The first recommended paper by Vignaud *et al.* reports a successful observation of the quantum Hall supercurrent, as measured by its periodicity with the magnetic field. The main change compared to the previous works appears to be the focus on devices with a typical linear size of under 200 nm, as opposed to the micron-scale devices used in previous works. The authors observe both the critical current with the right periodicity, and its rapid decay with the sample size. While I am convinced by the claim, contrasting the finding with the earlier experiment [7] leads to an interesting question. Specifically, if there is non-chiral conduction coexisting in parallel, why is the higher periodicity contributed by these edge states not seen in the new work?

The second paper by Uday *et al.* focuses on the nonlocal conductance, but replaces the quantum Hall sample with a quantum anomalous Hall insulator V-doped $Bi_xSb_{1-x}Te_3$. Because a quantum anomalous Hall insulator provides chiral conduction without magnetic field, using it should allow one to avoid the detrimental effect of superconducting vortices. The authors observe the negative conductance, and compare it with tight-binding simulations in this material. The simulation does demonstrate negative nonlocal conductances for some parameter ranges, however it also shows that the effect requires careful selection of the device geometry, with normal transmission frequently dominating over Andreev reflection. This property of the theory agrees well with the fragile nature of nonlocal processes, seen both in the first paper, and in the earlier works on graphene [4]. The new experiment leaves the question of the microscopic origin of the systematically negative conductance open. Yet, I think it offers some evidence that dissipation into the vortices, considered in Ref. [3] may not be its main source: the quantum anomalous Hall insulator allows to carry out the experiment without an external magnetic field, which should remove most vortices.

In summary, the two works are important contributions to the field: one reports the predicted supercurrent, while the other utilizes a promising new material platform. Still, both works leave open questions that I hope will be addressed in the future.

References

[1] Virtual Science Forum workshop "Andreev reflection in quantum Hall systems: 2021 state of the union" https://virtualscienceforum.org/arqh/.

[2] Inducing superconducting correlation in quantum Hall edge states, G.-H. Lee, *et al.*, Nat. Phys. **13**, 693 (2017).

[3] M. Hatefipour *et al.*, "Induced Superconducting Pairing in Integer Quantum Hall Edge States", Nano Lett., **22**, 15, 6173 (2022).

[4] L. Zhao *et al.*, "Interference of chiral Andreev edge states", Nat. Phys. **16**, 862 (2020).

[5] A. L. R. Manesco, I. M. Flór, C.-X. Liu, A. R. Akhmerov, "Mechanisms of Andreev reflection in quantum Hall graphene", SciPost Phys. Core **5**, 045 (2022).

[6] V. D. Kurilovich, Z. M. Raines, L. I. Glazman, "Disorder-enabled Andreev reflection of a quantum Hall edge", Nat. Commun. **14**, 2237 (2023).

[7] A. Seredinski *et al.*, "Full control of quantum Hall supercurrent in a side gated graphene Josephson junction", Science Advances, **5**, eaaw8693 (2019).