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A New Twist on High-T$_c$ Superconductivity

1. **Twisted van der Waals Josephson Junction Based on a High-T$_c$ Superconductor**
   Authors: Jongyun Lee, Wonjun Lee, Gi-Yeop Kim, Yong-Bin Choi, Jinho Park, Seong Jang, Genda Gu, Si-Young Choi, Gil Young Cho, Gil-Ho Lee, and Hu-Jong Lee
   Nano Lett. 2021, **21**, 10469-10477

2. **Emergent Interfacial Superconductivity between Twisted Cuprate Superconductors**
   Authors: S. Y. Frank Zhao, Nicola Poccia, Xiaomeng Cui, Pavel A. Volkov, Hyobin Yoo, Rebecca Engelke, Yuval Ronen, Ruidan Zhong, Genda Gu, Stephan Plugge, Tarun Tummuru, Marcel Franz, Jedediah H. Pixley, and Philip Kim
   arXiv:2108.13455

3. **Doping a Moiré Mott Insulator: A t-J Model Study of Twisted Cuprates**
   Authors: Xue-Yang Song , Ya-Hui Zhang, and Ashvin Vishwanath
   Physical Review B **105**, L201102 (2022)

Recommended with a Commentary by Leonid I. Glazman, Yale University

Josephson junctions made of high-T$_c$ materials sound very much like 1990s. In fact, the dc Josephson effect was instrumental in establishing the d-wave nature of the high-T$_c$ superconducting order parameter. Recent developments reported in the recommended works, along with the reviewed earlier [1] papers [2] and [3], offer a new twist to the story: an attempt to harness the nature-given d-wave superconductivity of $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) to engineer and probe even more exotic superconducting order parameters.

Bi-2212 is a layered van der Waals crystal. A single-cell-thick layer of the material is confined on both sides by BiO planes, which makes it cleavable. A single layer of Bi-2212 was isolated, without degrading the superconducting transition temperature, in 2019 [1]. Recommended Paper 1 reported a success in fabrication of junctions with a controlled twist angle θ between two Bi-2212 layers and provided an indirect evidence for the Josephson coupling between the layers. The measured current-voltage characteristics were consistent with the presence of a θ-dependent Josephson critical current J_c. Further evidence for the Josephson coupling came from observation of the Shapiro steps in the current at characteristic voltages separated by $hf/2e$ from each other. The Shapiro steps develop under irradiation of the junction by microwaves with frequency f. The observed step separation indicated the charge transfer in lumps of $2e$ corresponding to single Cooper pairs. The critical current

$J_c(\theta)$ was maximal at $\theta = 0°$ and $\theta = 90°$, while $J_c(\theta)$ was undetectable at $\theta = 45°$. This is consistent with a simple symmetry argument [1]: At $\theta = 45°$, the order parameter in one layer (let us call it $d_{x^2-y^2}$) is even under a mirror reflection in a plane orthogonal to the layers, while the order parameter in the other layer, viewed in the same reference frame, is of the d_{xy} type and therefore odd under the same transformation. That leads to the suppression of charge transfer by Cooper pairs, tunneling one by one across the junction.

A stronger link between the layers enables pair co-tunneling, *i.e.*, transfer of multiple, say two, Cooper pairs in a single act of tunneling. In the absence of the conventional Josephson coupling, these processes take the central stage at $\theta = 45°$. There are several consequences of such higher-order coupling between the layers [1]-[3]. The two-pair co-tunneling transfers charge in lumps of $4e$. That, in turn, cuts in half the spacing between the Shapiro steps, as well as the period of the current-phase relation $J(\varphi)$ for the superconducting current between the layers. Changes in $J(\varphi)$ affect the pattern of the Fraunhofer oscillations in the critical current with an applied in-plane magnetic field. On a more profound level, the second-order co-tunneling facilitates a coherent superposition of $d_{x^2-y^2}$ and d_{xy} orders. The energetically-winning configuration [2], $d_{x^2-y^2} + i d_{xy}$, is characterized by a finite gap at all momenta, and – more importantly – corresponds to a phase with a spontaneously-broken time-reversal symmetry (TRS). This phase survives in some range of twist angles around $\theta = 45°$. Reviving the ideas thoroughly discussed [4] in 1990s, theoretical work [2] boldly predicted the transition temperature for the TRS-breaking state at optimal angle $\theta = 45°$ to coincide with a single-layer T_c and a survival of the state for θ deviating from the optimal twist by at least $\pm 15°$.

The theoretical ideas were put to test in the experiment performed on twisted Bi-2212 junctions and reported in Recommended Paper 2. At $\theta = 0°$, the measured Josephson critical current density was similar to that of intrinsic inter-layer junctions in the bulk Bi-2212. This attests to a substantial improvement of the assembled junctions quality compared to those used in Recommended Paper 1. The clearest confirmation of the Cooper pair co-tunneling came from the observation in Recommended Paper 2 of the fractional ($hf/4e$) Shapiro steps. These were detected only in the junction with θ closest to 45°. Variation of θ brought also visible changes to the Fraunhofer pattern at θ approaching 45°. These were harder to interpret because of the uncertainty with the area encircled by the superconducting current. The critical current density measured at $\theta = 44.9°$ was almost two orders of magnitude lower than its value at $\theta = 0$. At $\theta = 29°$ and the lowest temperature T of the experiment, the measured J_c was substantially lower than the expectation of the theory developed in the same paper. Overall, the experiment was a significant step towards realizing a novel superconducting state, but did not produce a "smoking gun" evidence for it.

A part of the challenge lies with the theory: it is important to develop realistic expectations for the range of θ and T favoring the putative TRS-breaking phase and suggest experimentally-realizable tests sensitive to the symmetry breaking. Theory presented in Recommended Paper 3 offers an answer to the call. An important advance made in this work is accounting for the electron tunneling form-factors dictated by the symmetry of the involved atomic orbitals [5]. The very same symmetry that favors the exotic superconducting phase at $\theta = 45°$ by forbidding the single Cooper pair tunneling, suppresses also a direct one-electron tunneling between the active d-orbitals. Another important aspect Recommended Paper 3 touches upon is the effect of electron correlations on the inter-layer tunneling. Correlations make coupling between the Bi-2212 layers sensitive to their Oxygen doping level x. Acting together, these two effects drastically reduce the expected range of existence for the new superconducting phase from $\pm 15°$ down to $\pm 2°$, and may alter the expected band topology of the Bogoliubov quasiparticles from a non-trivial to the trivial one. The new theory also predicts the maximal gap and critical current J_c in the TRS-broken phase to be much smaller than their respective values at $\theta = 0$. Despite different predictions for the band topology, the prediction of TRS breaking is common for all the cited theories. Recommended Paper 3 suggests a measurement of the Kerr angle in the THz frequency range as a test for it.

Taken together, the recommended papers 1-3 show an exciting progress as well as flesh out the outstanding challenges on the road to exotic superconductivity in twisted high-T_c structures.

References

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