Layer-decoupled superconductivity in $SrTa_2S_5$

Evidence of striped electronic phases in a structurally modulated superlattice
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Recommended with a Commentary by Steven A. Kivelson[a] and Chaitanya Murthy[b,a], a) Stanford University; b) University of Rochester

Layer decoupling refers to a striking situation in which a bulk three-dimensional (3D) material develops 2D long-range or quasi-long-range order at a higher temperature, T_{2D}, than that at which full 3D order is observed, T_{3D}. In the intervening temperature range, $T_{2D} > T > T_{3D}$, the ordered state thus resembles decoupled, individually ordered layers.* This is most interesting when the decoupling is dynamical, i.e. when the normal state of the material at $T > T_{2D}$ cannot be similarly described in terms of decoupled layers (although it may already be highly anisotropic). Layer decoupling is particularly striking in a superconductor, where it manifests as an infinite resistivity anisotropy, such that the in-plane resistivity $\rho_{ab} = 0$ (within experimental error), while the out-of-plane resistivity $\rho_c > 0$. Such a situation is highly implausible for any conventional superconducting state, where the effective interplane Josephson coupling grows in proportion to the square of the in-plane correlation length. It is suggestive of significant geometric frustration of the interplane coupling, such as can arise in a pair-density-wave (PDW) state.

The recommended article by Devarakonda et al. [1] reports evidence of layer-decoupled superconductivity in a bulk van der Waals superlattice material, $SrTa_2S_5$. This material consists of alternating H-TaS_2 transition-metal dichalcogenide (TMD) layers and Sr_3TaS_5 spacer layers, with a spacing of $\approx$ 12Å. There is an incommensurate 1D structural modulation of the layers, with a wavelength $\lambda \approx 4.4$ nm. (See Figure 1). Intra-layer superconducting coherence emerges below $T_{2D} \approx 2.5$ K, while inter-layer coherence only sets in at $T_{3D} \approx 1.5$ K. Just above T_{2D}, the in-plane resistivity anisotropy (parallel versus perpendicular to the wavevector

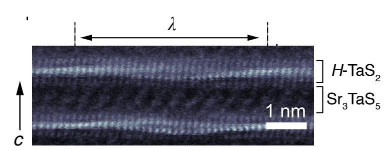

Figure 1: TEM cross-section of $SrTa_2S_5$ showing layered structure with 1D modulation. From Ref. [1].

*The same terminology may be applied even when true 2D order does not occur—for instance when due to the effect of weak disorder there is, below T_{2D}, a very long but finite in-plane correlation length.

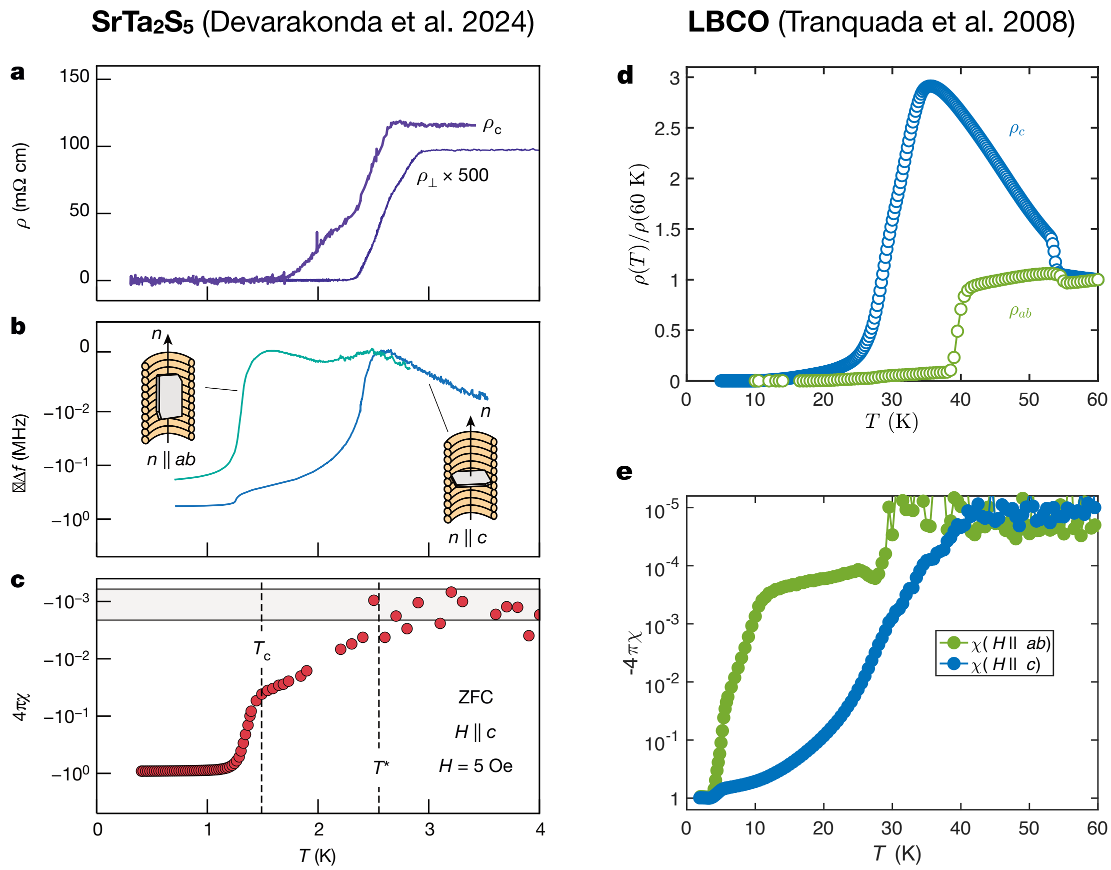

Figure 2: (a–c) Evidence of layer-decoupled superconductivity in $SrTa_2S_5$, from Ref. [1]: (a) electrical resistivity, (b) tunnel diode oscillator (TDO) frequency shift, and (c) magnetic susceptibility data. For the TDO measurements in panel b, the sample is placed in the inductive coil of an LC circuit; the resonant frequency f of the circuit then changes with the magnetic susceptibility of the sample. (d & e) Strikingly analogous evidence of layer-decoupled superconductivity in $La_{1.875}Ba_{0.125}CuO_4$, adapted from Ref. [2].

q of the stripe modulation) is $\rho_{\parallel}/\rho_{\perp} \approx 8$, while the out-of-plane anisotropy is $\rho_c/\rho_{\perp} \approx 500$. The measured in-plane resistivities, $\rho_{\parallel}$ and $\rho_{\perp}$, vanish simultaneously at around 2.3 K, while ρ_c remains nonzero until around 1.6 K (Figure 2a). Weak diamagnetism consistent with in-plane screening supercurrents onsets at $T_{\rm 2D}$, while inter-plane screening and perfect diamagnetism onset at $T_{\rm 3D}$ (Figure 2b,c). In the apparently layer-decoupled regime, the authors observe the expected 2D Berezenskii–Kosterlitz–Thouless (BKT) scaling of voltage V with in-plane current density I, $V \propto I^{\alpha(T)}$, and extract $T_{\rm BKT} \approx 1.9$ K at which the exponent $\alpha(T_{\rm BKT}) = 3$.

Strikingly analogous behavior has been seen in a number of stripe-ordered cuprate high temperature superconductors, most notably in 1/8 doped LBCO ($La_{1.875}Ba_{0.125}CuO_4$) [2, 3], as illustrated in the right panels (d & e) of Figure 2. Not indicated on the figure is a structural transition to a low-temperature tetragonal (LTT) phase that occurs at around 54 K, which in this material coincides with the charge stripe (CDW) ordering "transition" temperature,

T_{CDW}. Spin stripe (SDW) order onsets below a lower "transition" temperature, $T_{\text{SDW}} \approx 40$ K.[†] As imposed by the local symmetry of the LTT phase, the stripes run in perpendicular directions in neighboring copper-oxide planes. 2D superconducting correlations also onset at T_{SDW}, as evidenced by the sharp drop in the in-plane resistivity ρ_{ab} (panel d) and the onset of weak in-plane diamagnetism (panel e). ρ_{ab} becomes immeasurably small below approximately 20 K while the out-of-plane resistivity ρ_c remains substantial and only becomes immeasurably small below about 10 K. Perfect diamagnetism and the Meissner effect (from field-cooled data not shown) onset at a well-defined superconducting $T_c = 4$ K.

It was these observations of layer decoupling in various stripe-ordered cuprates that originally led to the conjecture that pair-density-wave (PDW) order can arise from strong correlations alone[‡] [4, 5]: Since a charge modulation with wavevector $\mathbf{q}$ can couple to a PDW with wavevector $\mathbf{q}/2$, the criss-crossed charge stripes in LBCO would naturally favor a 90° rotation of the PDW ordering vector between neighboring copper-oxide planes, and the leading interplane Josephson coupling would then vanish by symmetry.[§] The situation in $SrTa_2S_5$ is somewhat different in that there is no rotation of the stripe modulation between layers. The interlayer Joesphson coupling in a PDW state is then suppressed depending on the relative phase shift δ between charge stripes in neighboring layers, but only vanishes when $\delta = \pi$ (for a pure PDW). Notably, the authors of Ref. [1] deduce precisely that $\delta = \pi$ from analysis of electron diffraction data.

The observation of layer-decoupled superconductivity so reminiscent of that seen in the cuprates in a completely different material is, first and foremost, reassuring evidence that dynamical layer decoupling is a real phenomenon. It lends support to the PDW conjecture, as this could seemingly explain both sets of observations. Indeed, currently, without fine tuning, the only theoretically well understood route to dynamical layer decoupling of the sort observed here requires the existence of a "pure" PDW state (i.e. with no uniform component). However, apart from this experiment, we know of no other reason to assume the existence of such a phase in $SrTa_2S_5$. Further work is needed to either corroborate this assumption, or to discover other possible routes to layer decoupling. Importantly, the rather different energy and temperature scales involved in this new "PDW candidate material", as well as the differences in the nature of the interplane geometry (geometric frustration) which is presumed to be responsible for the layer decoupling, should allow for a variety of new experimental tests of the conjectured exotic order.

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[†] We have placed quotes on "transition" in cognizance of the fact that although both the CDW and SDW orders have large in-plane correlation lengths, these remain finite and the transitions are somewhat rounded.

[‡] I.e. it occurs even in the absence of Zeeman splitting of the electron dispersion that might give rise to the otherwise closely related FFLO (Fulde–Ferrell–Larkin–Ovchinnikov) superconducting state.

[§] An almost identical argument can be applied to account for the lack of interplane correlations of the spin stripes in LBCO, despite their long in-plane correlation lengths, i.e. the SDW order exhibits a form of layer decoupling as well.

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