Perfect Coulomb Drag in bilayer exciton systems

1. **Perfect Coulomb drag in a dipolar excitonic insulator**
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2. **Perfect Coulomb drag and exciton transport in an excitonic insulator**
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Most low-temperature properties of metals and semimetals are governed by the dynamics of Landau quasiparticles—fermionic excitations carrying electric charge e and spin 1/2—which form a degenerate Fermi gas. Upon further cooling, residual attractive interactions among these quasiparticles can drive the system into a superconducting phase. In contrast to this well-established paradigm of a charged degenerate Fermi gas, a charge-neutral degenerate Bose gas has almost never been realized in solid-state systems. A notable exception is provided by excitons formed between electrons and holes from different Landau levels residing in neighbouring quantum wells [1, 2].

Now, there is strong experimental evidence that a two-dimensional degenerate exciton gas can be realized without an external magnetic field in a novel class of devices formed by stacking two different transition metal dichalcogenide (TMD) monolayers [5]. In these structures, electrons and holes with equal densities are generated separately in the two layers and bind into excitons through the unscreened interlayer Coulomb interaction (see Fig. 1). A thin insulating hBN spacer between the layers suppresses direct electron–hole recombination, allowing the excitons to acquire sufficiently long lifetimes to thermalize and form an equilibrium Bose gas.

Such interlayer exciton systems were first explored in double–monolayer graphene devices [3, 4]. However, owing to graphene's large Fermi velocity—and the resulting low electronic density of states—the formation of a degenerate exciton Bose gas is difficult to detect at zero magnetic field. Clear signatures emerge only in the presence of a magnetic field, where both electrons and holes are quantized into Landau levels. In 2021, the first encouraging experimental evidence at zero magnetic field was reported from quantum capacitance measurements on a bilayer exciton device composed of WSe_2 and $MoSe_2$ monolayers [5]. A pronounced enhancement of the quantum capacitance was observed, providing strong indications of pairing correlations between electrons and holes.

Definitive "smoking-gun" experimental evidence for the formation of an interlayer exciton gas was subsequently reported in two papers published in Science last year, as listed above. Two independent U.S. research groups, one based at Cornell University and the other at the University of California, Berkeley, both observed nearly 100% Coulomb drag in bilayer exciton devices composed of WSe_2 and $MoSe_2$ monolayers. In a Coulomb drag experiment, a current driven through one layer (active layer) induces a current in the second, electrically isolated layer (passive layer) when the latter is placed in a closed circuit. If an interlayer exciton gas is formed such that nearly all electrons and holes are bound into excitons, the excitons become the only mobile carriers in the system. The flow of these neutral excitons necessarily generates charge currents of equal magnitude but opposite direction in the two layers, leading to a drag current in the passive layer that matches the driving current in the active layer—corresponding to a Coulomb drag ratio approaching 100%.

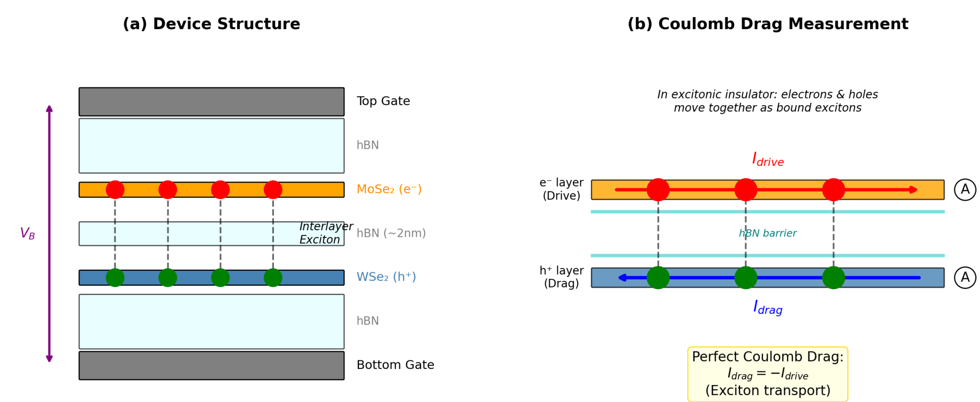

Figure 1: (a) Device structure of the bilayer exciton system. A $MoSe_2$ monolayer (electron layer) and a WSe_2 monolayer (hole layer) are separated by a thin hBN spacer (∼2 nm). Interlayer excitons form through Coulomb attraction between electrons and holes across the barrier. Top and bottom gates control the carrier densities via the bias voltage V_B. (b) Schematic of the Coulomb drag measurement. In the excitonic insulator phase, electrons and holes move together as bound excitons. A drive current I_{drive} in the electron layer induces an equal and opposite drag current I_{drag} in the hole layer, resulting in perfect Coulomb drag ($I_{\text{drag}} = -I_{\text{drive}}$).

Both groups claimed to see such perfect Coulomb drag in similar interlayer exciton devices under zero magnetic field but with different measuring techniques. The first paper (Nguyen et al.) uses direct electrical transport with independently contacted electron and hole layers. It demonstrates perfect counterflow currents and shows that the drag ratio remains above 0.9 up to ∼20 K. Crucially, by tuning the pair density, it reveals a sharp exciton Mott transition, where perfect drag collapses abruptly and conventional frictional drag emerges, allowing a detailed mapping of the EI-to-metal transition and its critical behavior. The focus is on thermodynamic phase boundaries and density-driven transitions in equilibrium exciton fluids.

In contrast, the second paper (Qi et al.) avoids electrical contacts altogether and instead uses optical detection of ac transport, enabling access to the intrinsic transport properties without contacts. While it also observes perfect Coulomb drag in the excitonic insulator phase, it goes further by extracting an explicit exciton resistance through frequency-dependent measurements. This leads to a key qualitative conclusion absent in the first work: perfect drag does not imply superfluidity. The exciton current is shown to be dissipative, with no evidence for an exciton superfluid down to 2 K, likely due to disorder or the strong phase fluctuation due to the Berezinskii–Kosterlitz–Thouless transition nature.

For the first time in condensed-matter physics, a promising two-dimensional exciton fluid has been realized that is thermodynamically stable, highly mobile, and operates far away from the quantum Hall regime of either electrons or holes. Beyond the already reported near-perfect Coulomb drag, this new quantum fluid is expected to give rise to a variety of novel transport phenomena. First, since an exciton carries zero net charge, an exciton current does not transport electrical charge but instead carries energy. As a result, exciton transport can make a significant contribution to thermal transport, including the thermal conductivity. Second, although excitons are composite particles, their internal degrees of freedom remain active even in the Bose–Einstein condensation (BEC) limit, where electrons and holes are strongly bound. Owing to the coupling between the center-of-mass motion and the internal dynamics of excitons, exciton currents can respond to external magnetic fields, leading to a range of unconventional phenomena, such as the exotic nondissipative inverse dipole Hall effect in the superfluid phase [6], as well as new mechanisms for thermal Hall and Seebeck/Nernst effects. Third, the interlayer exciton device geometry naturally breaks inversion symmetry. When electron and hole states residing in different layers are strongly coupled to form interlayer excitons, this broken inversion symmetry can give rise to sizable nonlinear optical responses.

References

[1] J. P. Eisenstein, G. S. Boebinger, L. N. Pfeiffer, K. W. West, and Song He, Phys. Rev. Lett. **68**, 1383 (1992).

[2] J. P. Eisenstein and A. H. MacDonald, Nature **432**, 691 (2004).

[3] X. Liu, K. Watanabe, T. Taniguchi, B. I. Halperin, and P. Kim, Nat. Phys. **13**, 746 (2017).

[4] X. Liu, J. I. A. Li, K. Watanabe, T. Taniguchi, J. Hone, B. I. Halperin, P. Kim, and C. R. Dean, Science **375**, 205 (2022).

[5] L. Ma, P. X. Nguyen, Z. Wang, Y. Zeng, K. Watanabe, T. Taniguchi, A. H. MacDonald, K. F. Mak, and J. Shan, Nature **598**, 585 (2021).

[6] Y. Shao, H. Shi, and X. Dai, arXiv:2509.02142 (2025).