Beyond Trions: When Excitons Couple Simultaneously to *Multiple* Distinguishable Fermi Seas

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When doped with a high density of mobile charge carriers, the monolayer transition-metal dichalcogenide (TMD) semiconductors can host new types of composite many-particle exciton ground states that do not exist in conventional semiconductors. Recently, we demonstrated that such many-body bound states arise when a photoexcited electron-hole pair couples to not just a single Fermi sea that is quantum-mechanically distinguishable (as for the case of conventional charged excitons or trions), but rather couples *simultaneously to multiple* Fermi seas, each having distinct spin and valley quantum numbers [1-3].

Composite six-particle "hexcitons" were first identified recently in electron-doped WSe_2 monolayers [1-3], but under suitable conditions they should also form in <u>all other members</u> of the monolayer TMD family. Here we present new spectroscopic evidence [4] for the emergence of many-body hexcitons in charge-tunable WS_2 monolayers (where they form at the A-exciton resonance, similar to WSe_2,) and in $MoSe_2$ monolayers (where they form only at the B-exciton). The difference is due to the ordering of the spin-orbit-split conduction bands; see Figure for details. These studies used dual-gated TMD monolayers, assembled via van der Waals stacking on single-mode optical fibers to enable circularly-polarized absorption spectroscopy in high magnetic fields to 60 T. Interestingly, high magnetic fields can force, via the valley Zeeman effect, the filling of a *third* reservoir of electrons in WSe_2, leading to the formation of an eight-particle "oxciton" state wherein a photoexcited *e-h* pair couples simultaneously to three electron Fermi seas with distinguishable quantum numbers.

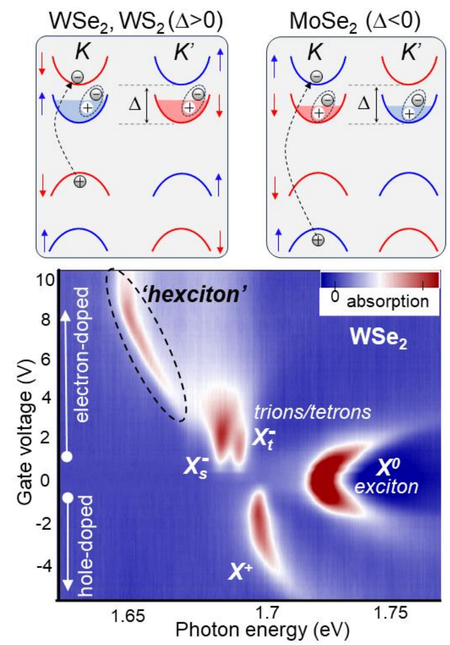

Fig: Six-particle "hexcitons" emerge at high electron doping in WSe_2 monolayers, when photoexcited *e-h* pairs couple to *both* of the quantum-mechanically distinguishable Fermi seas in the lower conduction bands. In $MoSe_2$, hexciton ground states appear at the B-exciton.

We emphasize that these composite hexcitons are <u>optically-allowed ground states</u> of the interacting exciton–Fermi sea system and are therefore distinct from the many types of optically-forbidden dark excitons and trions that appear only in photoluminescence studies and, moreover, should not be confused with multiexciton complexes (e.g., biexcitons) that emerge only at higher photoexcitation intensity. Finally, we argue that robust many-body hexciton ground states should *always* appear in hole-doped TMD monolayers at the B-exciton [4], which is supported by our own measurements and by data published in the literature.

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[2] D. Van Tuan, S.-F. Shi, X. Xu, & S. A. Crooker, H. Dery, Six-body and Eight-body Exciton States in Monolayer WSe_2, *Phys. Rev. Lett.* **129**, 076801 (2022).

[3] D. Van Tuan & H. Dery, Composite excitonic states in doped semiconductors, *PRB* **106**, L081301 (2022).

[4] J. Choi, J. Li, D. Van Tuan, H. Dery, & S. A. Crooker, Emergence of composite many-body exciton states in WS_2 and $MoSe_2$ monolayers, *Phys. Rev. B* **109**, L041304 (2024).