Doping-Induced Brightening of Dark Excitons and Trions in a WSe_2 Monolayers

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Semiconducting transition metal dichalcogenides (S-TMDs) are a remarkable class of layered van der Waals materials that have attracted significant attention over the past decade. A key classification of S-TMDs monolayers (MLs) is based on their excitonic band structure. They can be classified as bright or darkish materials. WSe_2 ML is one of the most studied darkish S-TMD, with well-characterized optical responses and excitonic behaviour [1]. The visibility of the dark excitons and dark trions can be significantly changed by tuning the doping level of the ML, which influences the balance of neutral and charged excitonic species [2]. However, a fundamental aspect, such as a magnetic-field-induced brightening of dark neutral and trions, has remained elusive.

To explore this phenomenon, we fabricated a device consisting of a high-quality WSe_2 ML encapsulated in hexagonal boron nitride (hBN) and embedded with a graphene contact attached to the ML and below the bottom hBN flake. This configuration allows us to investigate the photoluminescence (PL) of the WSe_2 ML at low temperature (T=5 K) as a function of the gate voltage, which is equivalent to changes in free carrier concentration.

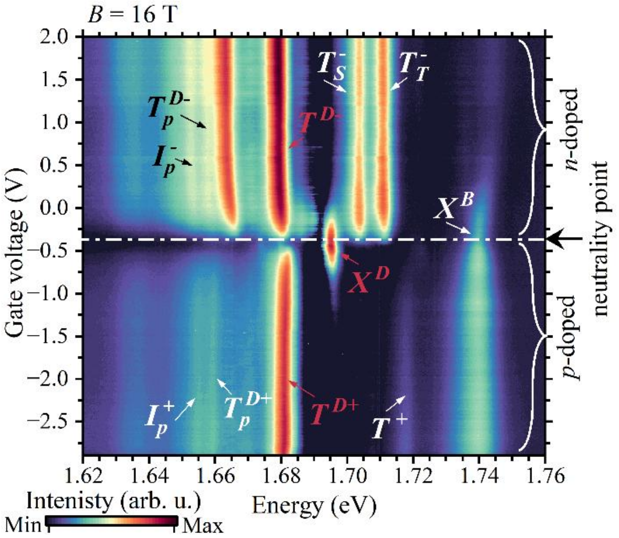

Figure: False-color map of the voltage-dependent PL spectra of the WSe2 ML doping.[3]

The Figure presents the false-color map of the PL intensity as a function of gate voltage. This configuration allows precise electrostatic doping through gate voltage, as seen in Figure 1. Three distinct regions of doping can be identified (neutral, n- and p-doped), which are correspondingly accompanied by the appearance of the bright neutral excitons (XB), bright negative (TS and TT) and positive (T+) trions. The emissions of the dark excitons and trions are barely visible. Therefore, we measured PL spectra under in-plane magnetic fields up to 16 T (Voigt geometry), while systematically varying the doping level. When the desired doping levels are achieved, the applied magnetic field mainly enhances the emission from dark excitonic states, accompanied with the given free carrier concentration (both sign and magnitude).

Our results reveal previously unobserved optical signatures of spin–valley interactions in dark neutral excitons and dark trions, addressing a key question in the dynamics of S-TMD excitons and offering insights for future valleytronic device design.

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[3] G. Krasucki, et al., *arXiv*:2604.25553 (2026).