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A phenomenological theory of dark exciton reservoirs in monolayer transition metal dichalcogenides

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Abstract: Dark excitons play a decisive role in governing the low-temperature optical and dynamical properties of monolayer transition metal dichalcogenides (TMDs). Owing to their spin- and momentum-forbidden nature, dark excitons possess long lifetimes and remain weakly coupled to light, rendering their direct experimental detection challenging. Nevertheless, a surge of recent experiments demonstrates that dark excitons act as long-lived population reservoirs that strongly influence bright exciton photoluminescence, relaxation pathways, and nonequilibrium dynamics. In this work, we develop a comprehensive phenomenological framework describing coupled bright and dark exciton populations using rate equations that incorporate phonon-mediated scattering. Analytical expressions for steady-state densities, temperature-dependent photoluminescence, and characteristic relaxation times are derived. The model captures a wide range of experimental observations, including emission quenching at low temperatures, thermal brightening, and bi-exponential decay dynamics. Beyond reproducing known trends, the framework provides physical insight into how dark excitons control excitonic response in two-dimensional semiconductors and offers a flexible platform for exploring collective and nonlinear dark-exciton-driven phenomena.

Keywords: Dark excitons, Exciton dynamics, Dark reservoir, Transition metal