

Manipulation of quantum dynamics at extremely ultrafast time scales

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Ultrafast control of electronic and valley degrees of freedom is a defining challenge for next-generation quantum electronics, where device functionality is fundamentally constrained by band structure and symmetry. In this talk, I show that light-wave engineering enables qualitatively new nonequilibrium quantum states and unprecedented control of charge and valley dynamics at femtosecond and sub-femtosecond time scales. I first demonstrate that circularly polarized light can drive graphene into novel nonequilibrium steady states, including Floquet Chern insulators and radiation-induced zero-resistance states. At low driving frequencies, the system develops negative longitudinal resistance, triggering a spontaneous breakdown into inhomogeneous current patterns and an emergent zero-resistance phase, revealing a new class of light-driven quantum matter far from equilibrium. I then introduce a fundamentally new light-wave valley selection rule that breaks the long-standing binary paradigm of K and K' valley control in transition metal dichalcogenides. By coherently combining circularly polarized pump and linearly polarized driver pulses, I achieve deterministic, near-unity polarization of any single Q valley within the sixfold-degenerate Q-valley manifold of monolayer MoS₂, fully decoupled from K and K' valleys. This control persists across an exceptionally broad ultrafast window, from terahertz to petahertz frequencies. These results position tailored light fields as a universal and scalable platform for ultrafast transport control and multistate valleytronic architectures, pushing condensed-matter systems to their extremely ultimate dynamical limits.