Spin – Charge Conversion and Topological Phases in Proximitized Graphene Heterostructures

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Graphene-based van der Waals (vdW) heterostructures constitute an effective platform for inducing spin–orbit coupling, exchange interactions, and symmetry breaking via proximity effects, while preserving the electronic properties of graphene [1-3]. This provides a route to engineering spin-dependent transport and topological phenomena in Dirac materials. In this talk, I will present recent theoretical results on proximitized graphene, focusing on heterostructures combining graphene with transition-metal dichalcogenides (TMDs) and magnetic transition-metal halides (TMHs).

Building on our first-principles and effective-model studies of graphene-based vdW heterostructures, we show that electrostatic gating, twist angle, and strain can shift the graphene Dirac cones into the band gap of adjacent insulating layers (e.g., CrI_3, $CrBr_3$, MoS_2, and WSe_2), thereby enabling a tuneable proximity regime. In this regime, the interplay of exchange interactions and symmetry-allowed spin–orbit fields leads to topological and valley-dependent phenomena, as well as efficient spin–charge conversion [3–7]. The corresponding low-energy effective Hamiltonians provide an accurate description of proximitized graphene and enable a systematic analysis of spin-dependent transport and Berry-curvature effects.

I will further consider graphene on semiconducting TMDs [5-7] and the so-called 'ex-so-tic' vdW heterostructures [8,9], focusing on how spin–charge conversion efficiency and valley-dependent responses can be tuned via twist angle and electrostatic gating. Within linear-response theory, we identify regimes in which current-induced spin polarization, as well as anomalous and spin Hall effects, are significantly enhanced, and show that the valley Hall conductivity can approach quantized values in appropriate parameter ranges. We also address proximity-induced topological phases in graphene–TMH heterostructures, including the conditions required to realize Chern insulating states and their evolution under twist, gating, and strain [4,5,7,10–12]. Finally, I will briefly overview main concepts for spin–orbit torque devices based on vdW heterostructures [13-16].

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