Nanophotonic control of quantum phenomena in low dimensional materials

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Electrons quantum-mechanically confined in low-dimensional materials, such as graphene, transition metal dichalcogenides (TMDs), hexagonal boron nitride (hBN), and carbon nanotubes, exhibit unusual properties not found in bulk materials [1], including relativistic electronic behavior governed by the Dirac equation, superconductivity, moiré physics, valleytronics, and quantum plasmons. These novel quantum phenomena can also be controlled via light-matter interactions at the nanoscale.

In this talk, we introduce our recent work on the interfaces between nanophotonics and low-dimensional materials. First, we theoretically elucidate the mechanism behind the control of valley polarization in 2D TMDs coupled to nanophotonic structures [2]. The conventional Purcell effect describes how nanophotonic structures modify the density of states (DOS) of a quantum system, thereby altering its spontaneous decay rate. However, we show that optical spin-dependent modification of DOS must be considered to achieve valley-selective control. We introduce the concept of the "valley Purcell effect" to describe the valley-selective manipulation of exciton populations in 2D TMDs via resonant nanophotonic structures. We also provide a theoretical framework to guide the realization of room-temperature perfect valley polarization.

In the second part of the talk, we present the nanophotonic control of 1D quantum plasmons, namely, Luttinger liquid plasmons, via the plasmonic environment provided by graphene. In paramagnetic 1D metals, electrons behave as strongly correlated electronic matter known as a Luttinger liquid, rather than as quasi-free electrons. The Luttinger liquid exhibits intriguing quantum phenomena, such as the absence of quasiparticles, spin-charge separation, and electron-photon conversion. However, these quantum properties are not tunable by gating, posing significant challenges for realizing active quantum optoelectronic devices. Here, we demonstrate that the plasmon wavelength of 1D quantum plasmons can be tuned by coupling to graphene. Since graphene plasmonic properties are tunable via electrostatic gating, the coupled graphene environment effectively modulates the 1D Luttinger liquid plasmons. Real-space near-field profiles of the 1D quantum plasmons were imaged using infrared scattering-type near-field optical microscopy (IR-SNOM), and experimental results show excellent agreement with predictions.

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