Spectroscopy of strongly correlated electrons in atomically-thin materials

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When the strength of Coulomb interaction E_C between itinerant electrons in a two-dimensional system becomes significantly larger than the kinetic energy E_F, the electrons start to develop strong correlations. A paradigm phase that is expected to emerge in this regime is an electronic Wigner crystal (WC) [1], in which the electrons spontaneously form a periodic lattice mimicking that of the real crystals. In order for such a crystallization to occur in the absence of the magnetic field $B = 0$, the ratio of the two energy scales $r_s = E_C/E_F$ must exceed 30. Owing to severe difficulties in satisfying this condition for conventional semiconductors (e.g., GaAs), prior experimental studies of electronic solid have been mainly focused on the electrons occupying a single Landau level under the influence of a strong external *B*-field, where the kinetic energy is almost completely quenched.

Recently, atomically-thin transition metal dichalcogenides (TMDs) have emerged as a highly-tunable experimental platform that unlocks the access to uncharted territories of strongly correlated electron physics. This is due to reduced dielectric screening and large carrier effective masses, which endow TMD monolayers with excellent optical properties and give rise to strong inter-electron interactions enabling to reach r_s values being more than an order of magnitude larger than that for the GaAs at comparable electron densities. In this talk, I will review our recent optical investigations of landmark correlated phases in charge-controlled TMD-based van der Waals heterostructures.

In the first part, I will present direct evidence that the electrons in a $MoSe_2$ monolayer at densities $< 3\times10^{11}$ cm^{-2} form a WC at $B = 0$ [2]. This is uncovered by our novel spectroscopic technique allowing us to detect a long-range charge order in an electronic state through the periodic potential it generates for the excitons [3]. In the presence of this potential, the excitons undergo a Bragg diffraction, which gives rise to the emergence of a Bragg-umklapp transition in the reflectance spectrum that heralds the formation of the WC state. I will also show that the phase transition between this solid state and an electron liquid in the presence of an external *B*-field is associated with a sizable change in the electron spin-valley relaxation dynamics, as revealed by our time-resolved pump-probe experiments [4].

The second part of the talk will be devoted to the optical spectroscopy of correlated electronic phases in graphene. Although these phases have been extensively investigated in prior transport studies, they have remained thus far optically inaccessible due to the lack of graphene bandgap. I will show that they can be all-optically probed with the use of Rydberg excitons in a proximal TMD monolayer that is separated from the graphene by a few-layer-thick spacer of hexagonal boron nitride. Owing to large Bohr radii of Rydberg excitons, their energies and spectral weights are sensitively dependent on the compressibility of adjacent graphene electrons. This allows us to sense the formation of fractional quantum Hall states in graphene with a similar sensitivity to that of state-of-the-art transport tools [5].

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