Mini-symposium C1
Valleytronics

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C1-01 Keynote
Valley contrasting chiral phonons in monolayer hexagonal lattices
Qian Niu

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In monolayer hexagonal lattices, two inequivalent valleys appear in the Brillouin zone. With inversion symmetry breaking, we find chiral phonons with valley contrasting polarization and intrinsic magnetic moment. At valley centers, there is a three-fold rotational symmetry endowing phonons with a quantized pseudo angular momentum, which includes spin and orbital parts. From conservation of the pseudo angular momentum, crystal momentum and energy, selection rules in intervalley scattering of electrons by phonons are obtained. Due to chiral valley phonons, one can also observe polarized infrared photoluminescence and a valley phonon Hall effect induced by a valley contrasting phonon Berry curvature. The valley-contrasting chiral phonons can have wide applications in valleytronics.

C1-02 Invited
Valley Physics Back to Three Dimensions
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Starting from Silicon, the valley degrees of freedom has been playing an important role in understanding the electronic and optical properties of materials. In the past decade, remarkable valley physics has been successfully explored in two dimensional materials with layered honeycomb lattices. In this talk, I will introduce, instead of concluding, the most recent studies of how the valley degrees of freedom emerge and play essential roles in the long wavelength physics of new topological states in three dimensions, in particular, topological mirror insulators, Weyl semimetals, and Weyl and Dirac superconductors.

C1-03 Invited
Intervalley coupling by quantum dot confinement potentials in transition metal dichalcogenide monolayer
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Transition metal dichalcogenide (TMD) monolayers are promising platforms for exploring valleytronics due to their unique physical properties. In practical applications such as quantum dots (QDs), the QD confinement potential will break the translational symmetry of the TMD monolayer and hybridize their valley degrees of freedom. This valley hybridization may significantly change the valley physics in the QD from its form in pristine TMD monolayer. An important issue is to make clear the degree of valley hybridization. Here we construct TMD QDs by imposing confinement potentials on extended TMD monolayers and systematically study the intervalley coupling in the QDs. Two methods, i.e. the envelop function method and real space tight binding, are used to study the intervalley coupling and they give consistent results. We find that the intervalley coupling in such QDs is generically weak, and hence valley hybridization shall be well quenched by the much stronger spin-valley coupling in TMD monolayers and the QDs can well inherit the valley physics of their pristine monolayers. We also discover sensitive dependence of intervalley coupling on the central position, the lateral length scale, the shape, and the orientation of the QD confinement potentials, which may possibly allow tuning of the intervalley coupling by external controls.

C1-04 Keynote
Goos–Hänchen shift and Imbert–Fedorov shift in Weyl semimetals
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When a beam of light (photons) is reflected at an interface, the wave nature of photons can result in spatial shifts at the interface in the plane of incidence (longitudinal shift) and normal to the plane of incidence (transverse shift), which are referred as Goos–Hänchen (GH) shift and Imbert–Fedorov (IF) shift, respectively. As the massless fermionic cousin of photons, Weyl fermions are expected to share some similar characteristics as photons. Here, we report the GH and IF effects in Weyl semimetals—a promising material—harboring low energy Weyl fermions. Our results show that GH effect in WSMs is analogous to that discovered in a 2D relativistic material—graphene; however, the IF effect has no 2D counterpart, since it is genuine a 3D effect. We emphasize that the IF shift is actually originated from the topological effect of the systems, and can further lead to valley-dependent anomalous velocities. Experimentally, the topological related IF shift can be used to measure the Berry curvature, and the valley-dependent anomalous velocities provide new ways for designing valleytronic devices of high quality.

C1-05 Invited
Charge and Spin Transport in 2D carbon allotropes and other layered compounds
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Because of its two-dimensional structure and exceptionally high charge carrier mobilities, graphene is a candidate for replacing silicon based transistors in future applications and using the valley degree of freedom new functionality can be envisaged [1]. To use graphene as well as related dichalcogenides for applications, it is necessary to be able to engineer the band gap and charge carrier density in this material. One promising approach to match this challenge is the intentional doping of graphene [2] as well as nanostructuring. We present the influence of nitrogen-doping on charge and spin transport in single layer graphene as well as turbostratic graphene [3] and compare doped and undoped samples grown by chemical vapour deposition (CVD). After transfer to Si substrates, all samples are characterised using Raman spectroscopy and magnetotransport and a strong dependence of the electronic structure on the doping is observed. In particular the magnetotransport properties and quantum transport effects, such as weak localization depend strongly on the materials properties. Finally we extend this study to dichalcogenides.


C1-06 Invited
Scanning Tunneling Spectroscopy of Transition Metal Dichalcogenides: Quasiparticle Gap, Critical Point Energies and Heterojunction Band Offsets
Chendong Zhang1, Yuxian Chen1, Amber Johnson1, Ming-Yang Li2,
As an emergent atomically thin electronic and photonic materials material, transition metal dichalcogenides (TMDs) has triggered intensive research activities toward understanding of their electronic structures. Here I will introduce a comprehensive form of scanning tunneling spectroscopy (STS) which allows us to probe details quasi-particle electronic structures of TMDs. More specifically, we show that not only the quasi-particle band gaps but also the critical point energy locations and their origins in the Brillouin Zone (BZ) can be revealed using this comprehensive form of STS. By using this new method, we unravel the systematic trend of the critical point energies for TMDs due to atomic orbital couplings, spin-orbital coupling and the interlayer coupling. Moreover, by combining the micro-beam X-ray photoelectron spectroscopy (micro-XPS) and STS, we determine the band offsets in planar heterostructures formed by dissimilar single layer TMDs (MoS$_2$, WSe$_2$, and WS$_2$). We show that both commutativity and transitivity of heterojunction band offset hold within the experimental uncertainty.

**C1-07 Keynote**

**Broken SU(4) Symmetry and The Fractional Quantum Hall Effect in Graphene**

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Since its discovery more than three decades ago, the fractional quantum Hall effect has been studied almost exclusively in the two-dimensional electron systems formed in GaAs/AlGaAs heterojunctions. However, recent improvements in the quality of graphene have revealed a rich landscape of fractional quantum Hall states in this material, heralding the beginning of a new chapter in fractional quantum Hall physics. The N=0 Landau level of graphene is endowed with an approximate spin-valley SU(4) symmetry. In this talk, I will describe a variational approach to understand how this symmetry is broken, which allows to construct trial incompressible ground states, their charged quasi-particles and compute their associated gaps.

**C1-08 Invited**

**Valley Splitting and Polarization by the Zeeman Effect in Monolayer MoSe$_2$**

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The band structure of monolayer MoSe$_2$ features two inequivalent, but degenerate K and K' valleys in its Brillouin zone, which form the direct gap in this material. It was predicted theoretically and demonstrated experimentally that this valley degree of freedom can be accessed by selective excitation with circularly polarized light. Although the bands in these two valleys are degenerate, they are related by time-reversal symmetry and, hence, have opposite magnetic moments. In this paper, we report results of magneto-optical spectroscopy of monolayer MoSe$_2$. We demonstrate through analysis of the circularly polarized components of the photoluminescence that a perpendicular applied magnetic field breaks the valley degeneracy through the Zeeman effect. In the case of doped samples, we further show that the valley splitting creates a valley polarization, i.e., an imbalance in charge between the valleys. We discuss the magnitude of the Zeeman shifts for the neutral and charged exciton species observed experimentally and compare these values to theoretical predictions.

**C1-09 Invited**

**Pseudo magnetic field and valley transport in strained graphene**

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(Unavailable at time of printing)