Talk Abstracts

Spins, Valleys, and Topological States in 2D and Layered Materials

The Ohio State University

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Invited Talks: 25 min presentation, 15 min Q&A discussion

Contributed Talks: 15 min presentation, 5 min Q&A discussion
Graphene and novel 2d materials offer new perspectives for spintronics [1]. Graphene can reach spin lifetimes of 1-10 ns, limited currently by spin flips off magnetic moments [2]. However, graphene has no band gap, so its spintronic applications will be limited as a highly efficient spin transfer channel. Heterostructures of graphene and two-dimensional transition-metal dichalcogenides (TMDC) are emerging as systems in which both orbital and spin properties can be controlled by gating, thus offering a materials basis for spintronic applications, such as bipolar spin devices [3]. We have proposed that graphene on TMDCs can be used in optospintronics [4], since the direct gap of TMDCs allows optical spin orientation, with the successive transfer of spin into graphene. But these van der Waals stacks also yield interesting fundamental physics. We have recently shown that graphene on WSe\textsubscript{2} exhibits an inverted band structure, which leads to helical edge states in graphene nanoribbons on WSe\textsubscript{2} [5], with a bulk spin-orbit gap of about 1 meV, which is giant when compared to 24 micro eV in pristine graphene. I will also mention our latest results on bilayer graphene on TMDCs.

I acknowledge support from EU Graphene Flagship and the DFG SFB 689.

1. W. Han, R. Kawakami, M. Gmitra, and J. Fabian, Nature Nanotechnology 9, 794 (2014)
Electrical Generation of Valley Magnetization in 2D Transition Metal Dichalcogenides

Jie Shan

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Electrons in two-dimensional (2D) Dirac materials such as gapped graphene and single-layer transition metal dichalcogenides possess a new two-fold valley degree of freedom corresponding to the K and K’ valleys of the Brillouin zone. The valley degree of freedom carries orbital magnetic moment. A net valley magnetization forms the basis for valley-based applications. Although the control of valley magnetization by circularly polarized light and by a vertical magnetic field has now become routine, the development of practical valleytronic devices requires the pure electrical control of valley magnetization. In this talk, I will discuss our recent experimental results on the generation of valley magnetization on the channel edges of monolayer and bilayer MoS$_2$ transistors by the valley Hall effect, and in the bulk of strained monolayer MoS$_2$ by the valley magnetoelectric effect.
Monday 10:40-11:20 (Invited)

Exciton Spectrum and Selection Rule in Gapped Chiral Fermion Systems

Di Xiao

Department of Physics, Carnegie Mellon University

The recent discovery of valley-dependent phenomena in monolayer transition dichalcogenides have provide a unique opportunity to study the optical phenomena in gapped Dirac fermion systems. In this talk I will discuss the energy spectrum and optical selection rule of excitons in gapped Dirac fermion system, focusing on the important role of the Berry phase and topological winding number. I will show that the Berry phase can modify the exciton spectrum, causing an energy splitting between opposite angular momentum state. Furthermore, the winding number can also affect the exciton optical selection rule, which is markedly different from excitons in conventional semiconductors.
Monolayer Magnets

Xiaodong Xu

Department of Physics, University of Washington

Since the discovery of graphene, the family of two-dimensional (2D) materials has grown to encompass a broad range of electronic properties. However, until recently 2D crystals with intrinsic magnetism were still lacking. Such crystals would enable new ways to study 2D magnetism by harnessing the unique features of atomically-thin materials, such as electrical control for magnetoelectronics and van der Waals engineering for novel interface phenomena. In this talk, I will describe our recent magneto-optical spectroscopy experiments on van der Waals magnets, chromium(III) iodide CrI$_3$. I will first demonstrate the existence of isolated monolayer semiconductor with intrinsic Ising ferromagnetism. I will then show the layer number-dependent magnetic phases. The magnetic ground state evolves from being ferromagnetic in a monolayer, to antiferromagnetic in a bilayer, and back to ferromagnetic in a trilayer and thin bulk. Lastly, I will discuss the emerging spin phenomena in monolayer WSe$_2$/CrI$_3$ ferromagnetic semiconductor heterostructures, including ferromagnetic control of valley pseudospin in WSe$_2$ via large magnetic exchange field, and optical analog of giant magnetoresistance effect.
In this talk, I will discuss a number of exfoliable magnetic materials that are currently available for incorporation into heterostructures and other nano-devices. These materials include Ising and Heisenberg ferromagnets, itinerant ferromagnets, antiferromagnets, and even a system that is proximate to a Kitaev spin liquid.
High Spin-Orbit Group 14 Graphane Analogues and Layered Zintl Phases as Novel Topological and Magnetic Materials

Josh Goldberger

Department of Chemistry, The Ohio State University

The group 14 Graphane analogues represent a unique class of covalently modifiable 2D topological phases, as there have been many recent exciting predictions of the existence of 2D quantum spin Hall behavior at room temperature in these materials. Here, we will describe our recent efforts in the creation and properties of hydrogen and organic-terminated group IV graphane analogues, from the topochemical deintercalation of precursor Zintl phases in order to create these topological phases. First, through the synthesis and characterization of a wide array of ligand terminated germanane analogues we have established experimental limits to which the electronic structure can be manipulated via surface chemistry. Second, we will discuss our recent efforts on the synthesis and properties of ligand-terminated Sn-contain graphane analogues to create systems that span from trivial insulators to 2D topological phases depending on the surface functionalization group. Finally, we will describe emerging discoveries on the existence of topological insulating and magnetic phenomena in our Sn-containing layered Zintl phase precursor materials.
Atomic-Scale Control of Graphene Magnetism Using Hydrogen Atoms

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Condensed Matter Physics Center (IFIMAC), Universidad Autónoma de Madrid, Spain

Incorporating magnetism to the long list of graphene capabilities has been pursued since its first isolation in 2004. In this talk I will show how we use a scanning tunneling microscope to explore and manipulate graphene magnetism at an atomic level. Our work shows how the absorption of single H atoms on graphene magnetizes the graphene regions around them. In contrast to common magnetic materials, where the magnetic moments are localized in a few angstroms, the induced graphene magnetic moments extend over several nanometers and present an atomically modulated spin texture. Our measurements also prove that the induced magnetic moments couple strongly at very long distances following a particular rule: magnetic moments sum-up or neutralize critically depending on the relative H-H adsorption sites [1].

Fig. 1. Left, STM topography of a single H atom chemisorbed in graphene. Right, STS measurements of the LDOS induced by the H atom, showing the appearance of a fully polarized peak at $E_F$, and of graphene.

References
STM Studies of the Surface Sensitivity of 2D Materials

Jay Gupta

Department of Physics, The Ohio State University

The isolation of 2D graphene from graphite flakes has led to a revolution in materials science, physics and solid state chemistry. Because 2D materials are all surface, coupling to chemical groups on the surface or an underlying substrate is especially important to understand. We grow graphene and new analogues based on other group IV elements (i.e., silicene, germanene, stanene), to study how covalent surface ligands can tune the electronic, magnetic and topological properties of the sheets. For example, we have developed a new method to hydrogen-terminate graphene, that may be promising for controlling the conductivity or magnetic properties. We also study the interactions of 2D sheets with metal substrates; changes in surface electronic structure provide insight into the physics of electrical contact to this new class of materials.
Among transition metal dichalogenides (TMDs), monolayer tungsten disulfide (WS\textsubscript{2}) is gaining interest due to its large band gap, relatively high charge carrier mobilities and high spin-orbit coupling. The possibility to tune the electronic, optical and spin-valley related properties by substrate and adatom (e.g. alkali doping) engineering are one of the most interesting yet unexplored areas of research in the field of TMDs. Recently, we investigated the electronic band structure of monolayer WS\textsubscript{2} on h-BN by angle-resolved photoemission (ARPES). The 10\(\mu\)m sized spatial resolution of the \(\mu\)ARPES endstation at the newly commissioned MAESTRO facility of the Advanced Light Source allowed us to identify these flakes and to obtain high quality band structure and core level information in a full spectro-microscopic approach. Upon electron doping via in-situ surface potassium deposition, we observe an unexpected giant renormalization of the SL WS\textsubscript{2} valence band (VB) spin-orbit splitting from 430 meV to 660 meV, together with a band gap reduction of at least 325 meV. These findings suggest that the electronic, spintronic and excitonic properties are widely tunable in 2D TMD/h-BN heterostructures, as these are intimately linked to the quasiparticle dynamics of the materials.
The problem of unconventional magnetism in materials without d and f electrons has attracted continuous attention. We have measured the magnetoresistance (MR) of graphene at low temperature with in-situ hydrogenation in ultra-high vacuum environment. In the low field regime, we observed a cross-over from weak localization to weak anti-localization that provides evidence for magnetic moment created by hydrogen atom absorbed on graphene and such absorption also drastically increase the spin orbit coupling of graphene. In the high field regime, large non-saturating negative MR was found in hydrogenated graphene which could be tuned by carrier density and sample temperature. Such negative MR could also be the manifestation of local moments created by atomic hydrogen absorbed on graphene.
Long electron spin lifetimes are an important prerequisite for enabling advanced spintronic devices. In this respect the 1-ns benchmark is of high technological interest as it marks the threshold at which manipulation of spins with electrical high frequency technology becomes feasible (1 ns @ 1 GHz). For a long time, the measured spin lifetimes were shorter than 1 ns. Here we report on a major improvement in device fabrication which pushes the spin lifetimes to 12.6 ns in single layer graphene spin transport devices at room temperature which results in spin diffusion lengths as long as 30.5 \( \mu \text{m} \) [1]. This is accomplished by the fabrication of Co/MgO-electrodes on a Si/SiO\(_2\) substrate and the subsequent dry transfer of a graphene/hexagonal boron nitride (hBN) stack on top of this electrode structure where a large hBN flake is needed in order to diminish the ingress of solvents along the hBN-to-substrate interface. We demonstrate that the spin lifetime does not depend on the contact resistance area products in these devices, indicating that spin absorption at the contacts is not the predominant source for spin dephasing which may pave the way towards probing intrinsic spin properties of graphene. In the second part, we summarize our effort to replace natural by synthetically grown graphene [2]. We report on an advanced transfer technique that allows both reusing the copper substrate of the CVD graphene growth process and making devices with carrier mobilities as high as three million cm\(^2/\text{Vs}\) [3] thus rivaling exfoliated "natural" graphene. This material quality allows truly ballistic experiments with electron mean free paths exceeding 28 \( \mu \text{m} \) which brings novel electron-optic devices into reach.


Spin and Hot-Carrier Transport in Graphene

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Graphene and other two-dimensional materials have rapidly established themselves as intriguing building blocks for spintronic applications. Due to weak spin-orbit coupling and a lack of hyperfine interaction with the predominant zero-spin isotope \textsuperscript{12}C, the spin lifetime in graphene was expected to be in the microsecond or even millisecond range. However, in contrast to these expectations, experiments have demonstrated spin lifetimes typically below 10 ns. In the first part of the talk, I will introduce the two main theoretical models that are currently being considered to explain such a fast spin relaxation. They are unique to graphene and involve either resonant scattering with magnetic centers or spin-pseudospin coupling and Rashba spin-orbit interaction. Regardless of the differences in the microscopic processes, I will show that both of these models are able to explain all of the main features found in classical spin transport experiments using nonlocal spin injection and detection methods. I will then discuss recent experimental efforts aiming at highlighting their peculiarities; in particular, at verifying whether the spin relaxation is anisotropic, which would be the hallmark of the presence of a dominant spin orbit field \cite{1,2}. In the second part of the talk, I will discuss the generation, propagation and detection of hot carriers in graphene using purely electrical means. I will show that because typical carrier cooling times can be similar to spin lifetimes, it is possible to implement nonlocal hot-carrier injection and detection methods analogous to those used for spin \cite{3}. In addition, I will present evidence that the spin propagation can be reinforced by the presence of hot electrons, suggesting that the remote spin accumulation can be enhanced using temperature gradients.

\cite{3} J. F. Sierra et al., \textit{Nano Lett.} 15, 4000 (2015)
Graphene-Based Spintronic Devices: From a 2D Spin Field Effect Transistor to a Spin-to-Charge Converter

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The integration of the spin degree of freedom in charge-based electronic devices has revolutionised both sensing and memory capability in microelectronics. Further development in spintronic devices requires electrical manipulation of spin current for logic operations. In this presentation we will show two examples of graphene-based devices that work along this direction.

The mainstream approach followed so far, inspired by the seminal proposal of the Datta and Das spin modulator [1], has relied on the spin-orbit field as a medium for electrical control of the spin state [2-4]. However, the still standing challenge is to find a material whose spin-orbit coupling (SOC) is weak enough to transport spins over long distances, while also being strong enough to allow their electrical manipulation. In our recent work [5], we demonstrate a radically different approach by engineering a van der Waals heterostructure from atomically thin crystals [6], and which combines the superior spin transport properties of graphene with the strong SOC of MoS$_2$, a transition metal dichalcogenide with semiconducting properties. The spin transport in the graphene channel is modulated between ON and OFF states by tuning the spin absorption into the MoS$_2$ layer with a gate electrode [5]. Our demonstration of a spin field-effect switch using two-dimensional materials identifies a new route towards spin logic operations for beyond CMOS technology. Furthermore, the van der Waals heterostructure at the core of our experiments opens the path for fundamental research of exotic transport properties predicted for transition metal dichalcogenides [7], in which electrical spin injection has so far been elusive.

An alternative way to exploit spin currents for logic operations is the recent proposal of a spin-orbit logic [8] which takes advantage of the discovery of new spin-to-charge conversion effects (spin Hall effect, Rashba-Edelstein effect, spin-momentum locking). Finding routes to maximize the conversion efficiency is thus crucial. We show how to achieve a very large spin-to-charge voltage output at room temperature by combining Pt with a graphene channel [9], opening up exciting opportunities towards the implementation of these spin-orbit-based logic circuits.

Strong Modulation of Spin Current in Bilayer Graphene by Static and Fluctuating Proximity Exchange Fields

Simranjeet Singh

Department of Physics, The Ohio State University

Two dimensional (2D) materials provide a unique platform to explore the full potential of magnetic proximity driven phenomena, which can be further used for applications in next generation spintronic devices. Of particular interest is to understand and control spin currents in graphene by the magnetic exchange field of a nearby ferromagnetic material in graphene/ferromagnetic-insulator (FMI) heterostructures. I will present the experimental study showing the strong modulation of spin currents in graphene layers by controlling the direction of the exchange field due to FMI magnetization [1]. Owing to clean interfaces, a strong magnetic exchange coupling leads to the experimental observation of complete spin modulation at low externally applied magnetic fields in short graphene channels. Additionally, we discover that the graphene spin current can be fully dephased by randomly fluctuating exchange fields. This is manifested as an unusually strong temperature dependence of the non-local spin signals in graphene, which is due to spin relaxation by thermally-induced transverse fluctuations of the FMI magnetization.

Tunable Pseudo-Zeeman Effect in Graphene

Nancy Sandler

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Mechanical strain influences dramatically the distribution and dynamics of charge carriers in graphene, as elegantly described by the concept of a pseudo-magnetic field. In addition to the Landau quantization, already observed experimentally [1], the pseudo-field introduces a Zeeman term, breaking the underlying chiral symmetry of the honeycomb lattice. In analogy with the spin alignment of an electron in a magnetic field, the pseudo-spin of graphene, can be oriented by a pseudo-magnetic field through this Zeeman term. The pseudo-spin polarization can be revealed as a sublattice symmetry breaking that can be tuned by appropriate straining of the membrane. Using the tip of a scanning tunneling microscope to produce controlled deformations, we demonstrate that it is possible to achieve redistributions of the local density of states of up to 30% between the two sublattices [2]. The observed pseudo-spin polarization scales with the lifting height of the strained deformation and is quantitatively reproduced by analytic models in the lattice (tight-binding) and the continuum (Dirac equation). These results add a key ingredient to the celebrated analogy of graphene charge carriers to ultra-relativistic Dirac fermions. Furthermore, the deduced fields of about 1000T could provide an effective THz valley filter, a basic element of valleytronic devices.

References

Topological and Straintronic Properties of Graphene/BN Heterostructures

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Recently a number of research groups have demonstrated placing graphene on hexagonal BN (hBN) with crystallographic alignment. This not only creates a protected environment yielding high-mobility devices, but also due to the moire superlattice formed in these heterostructures, an energy gap, secondary Dirac Points, and Hofstadter quantization in a magnetic field have been observed. In these systems, we observe a $\pi$ Berry's phase shift in the magneto-oscillations when tuning the Fermi level past the secondary Dirac points, originating from a change in topological pseudospin winding number from odd to even when the Fermi-surface electron orbit begins to enclose the secondary Dirac points.

Moreover, unlike three-dimensional solids, a two-dimensional atomic membrane such as graphene is extraordinarily flexible. This raises the possibility to use strain to alter the properties of graphene to create novel devices. Such devices are based on the ability of strain to create synthetic gauge fields in graphene, producing effective electromagnetic potentials. I will discuss our work investigating the electronic transport properties of individual nanoscale-diameter folds that form in graphene when placed on BN substrates. We find that they behave as one-dimensional quantum dots and electron waveguides. The observed behavior can be understood using theoretical modeling that accounts for the pseudomagnetic field created by the strain, which confines electrons laterally via an effective double-barrier potential but enables one-dimensional electron motion along the fold axis. Our observations confirm this theory, which also predicts that these folds transmit electrons belonging to each of the two inequivalent valleys in the Brillouin zone differently, acting as valley filters. This opens the door to strain-based devices that filter and select electrons by their valley index, towards valleytronics in analogy to spintronics.
Quantum Kinetic Theory of Chiral Anomalies

Allan MacDonald*

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I will discuss a general quantum kinetic theory [1,2] of transport and low-field magneto-transport in weakly disordered crystals. The theory fully accounts for the electric-field induced interband coherence that is responsible for the momentum space Berry curvature contribution to wave-packet dynamics, and for its interplay with Bloch state scattering and with the dynamics introduced by an external magnetic field. It also provides a simple and general procedure for expanding the linear response of the Bloch-state density matrix to an electric field in powers of magnetic field. As an illustration, I will explain some predictions of the theory when applied to single-layer transition metal dichalcogenides, and to three-dimensional conductors that exhibit chiral anomalies, i.e. the positive magneto-conductance quadratic that is common in systems with separate Fermi surface pockets surrounding distinct Weyl points.

![Figure 1: Schematic summary of the theory of the E parallel to B quadratic longitudinal magnetoconductivity \( \sigma_{zz}(B^2_z) \) of a Weyl semimetal. \( \langle n \rangle \) and \( \langle S \rangle \) are band diagonal and band off-diagonal Bloch state density matrices, and \( \tau \) and \( \tau_{\text{intra}} \) are intervalley and intravalley scattering times. \( \sigma_{zz}(B^2_z) \) is the sum of contributions from the chiral anomaly \( \sigma_{zz}^{CA}(B^2_z) \) and the Lorentz force: \( \sigma_{zz}(B^2_z) = \sigma_{zz}^{CA}(B^2_z) + \sigma_{zz}^{LF}(B^2_z). \)]

*In collaboration with: Dimi Culcer (School of Physics, The University of New South Wales) and Akihiko Sekine (Department of Physics, University of Texas at Austin)

References
Quantum Anomalous Hall Effect in the Magnetic Topological Insulator Thin Films

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The quantum anomalous Hall (QAH) effect can be considered as the quantum Hall (QH) effect without external magnetic field, which can be realized by time reversal symmetry breaking in a topologically non-trivial system [1, 2]. A QAH system carries spin-polarized dissipationless chiral edge transport channels without the need for external energy input, hence may have huge impact on future electronic and spintronic device applications for ultralow-power consumption. The many decades quest for the experimental realization of QAH phenomenon became a possibility in 2006 with the discovery of topological insulators (TIs). In 2013, the QAH effect was observed in thin films of Cr-doped TI for the first time [3]. Two years later in a near ideal system, V-doped TI, contrary to the negative prediction from first principle calculations, a high-precision QAH quantization with more robust magnetization and a perfectly dissipationless chiral current flow was demonstrated [4]. In this talk, I will introduce the route to the experimental observation of the QAH effect in above-mentioned two systems [3, 4], and discuss the zero magnetic field dissipationless edge current flow as well as the origin of the dissipative channels in the QAH state [5]. Finally I will talk about our recent progress on the QAH insulator-Anderson insulator quantum phase transition and its scaling behaviors [6].

References

Evidence for the Quantum Spin Hall Effect in the 1T’ Phase of Single-Layer TMD Materials

Mike Crommie

Department of Physics, University of California, Berkeley

The transition metal dichalcogenides (TMDs) exhibit a variety of behavior due to their strong spin-orbit coupling, electron-electron interactions, and electron-phonon coupling. This causes, for example, charge density wave ordering, superconductivity, and even Weyl semimetal behavior in different TMD materials. Recently the quantum spin Hall effect (QSHE) was predicted to occur in the 1T’ phase of several TMD materials when they are thinned down to a single layer [1]. I will discuss our recent efforts to test this prediction in single layers of WTe$_2$ and WSe$_2$ grown via molecular beam epitaxy. Using angle-resolved photoemission (Stanford, LBNL ALS) and scanning tunneling microscopy/spectroscopy (UC Berkeley, LBNL MSD), we have observed evidence for the QSHE in the form of band inversion and edge states. This work is a collaboration between UC Berkeley, Stanford, and LBNL researchers.

Spin and Charge Transport in Two-Dimensional Heterostructures

Jeanie Lau

Department of Physics, The Ohio State University

Two dimensional materials constitute an exciting and unusually tunable platform for investigation of both fundamental phenomena and electronic applications. Here I will present our results on transport measurements on high mobility monolayer few-layer graphene/BN devices. Using quantum Hall effects in graphene as injectors, filters and detectors, we observe robust long distance spin transport through the antiferromagnetic state in graphene. In another few-layer graphene system, ABA-stacked trilayer graphene consists of multiple Dirac bands, where crystal symmetry protects the spin degenerate counter-propagating edge modes resulting in \( \sigma_{xx} = 4e^2/h \). At even higher magnetic fields, the crystal symmetry is broken in by electron-electron interactions and the \( \nu=0 \) quantum Hall state develops an insulating phase. Our findings indicate the role of crystal and spin symmetry in generation of topological phases in multiple Dirac bands.
Motivated by recent experiments probing anomalous surface states of Dirac semimetals (DSMs) Na$_3$Bi and Cd$_3$As$_2$, we raise the question posed in the title. We find that, in marked contrast to Weyl semimetals, the gapless surface states of DSMs are not topologically protected in general, except on time-reversal-invariant planes of surface Brillouin zone. We first demonstrate this in a minimal 4-band model with a pair of Dirac nodes at $k=(0,0,\pm Q)$, where gapless states on the side surfaces are protected only near $k_z=0$. We then validate our conclusions about the absence of a topological invariant protecting double Fermi arcs in DSMs using a K-theory analysis for space groups of Na$_3$Bi and Cd$_3$As$_2$. Generically, the arcs deform into a Fermi pocket, similar to the surface states of a topological insulator (TI), and this can merge into the projection of bulk Dirac Fermi surfaces as the chemical potential is varied. We make sharp predictions for the doping-dependence of the surface states of a DSM that can be tested by ARPES and quantum oscillation experiments.
Line Nodes, Weyl Points and Orbitronics on the Triangular Lattice

Eugene Mele

Department of Physics and Astronomy, University of Pennsylvania

Interest in topological states of quantum matter has focused on the classification of topological but gapless electronic states, including Weyl and Dirac semimetals and various types of line node semimetals. Motivated by recently reported work on two-dimensional Cu$_2$Si which is a candidate 2D line-node semimetal, we study a model that supports a novel family of topological states on the primitive triangular lattice. Nontrivial k-space geometry emerges from propagation within an orbitally degenerate manifold (here the Si 3p-states) on the primitive lattice. We find that this model describes the expected line node degeneracies protected by z-mirror symmetry, but the L=1 pseudospin symmetry also requires the presence of both linear and multi-Weyl point degeneracies. Interestingly in these latter cases, topologically compensating point singularities enforced by the global symmetry of the band structure are generically offset in energy. We augment this model with T-breaking perturbations to identify the observable consequences of this unusual k-space texture for various dissipationless transverse responses including the anomalous Hall conductance and a related orbital Hall conductance.
In heterostructures made of two dissimilar materials, proximity coupling at the interface can have profound consequences on the physical properties of both. Numerous examples exist in condensed matter physics. I will present our recent work on proximity effects to induce spin-orbit coupling (SOC) and exchange interaction. In graphene/transition metal dichalcogenide (TMD) heterostructures, we have successfully induced up to 1.5 meV in Rashba SOC in graphene measured by quantum transport. To induce exchange interaction, we have exploited atomically flat rare-earth iron garnet films (e.g. yttrium iron garnet- YIG and thulium iron garnet- TIG) as the source of the exchange and demonstrated strong exchange interaction in graphene and the surface states of (Bi, Sb)$_2$Te$_3$ topological insulator. These two interactions are essential ingredients for realizing the quantum anomalous Hall state in both systems, which is very exciting for potential spintronic applications.
The Weyl semimetal (WSM) was recently discovered in solids (e.g. TaAs) with quasiparticle excitations as a counterpart of the high-energy particle, the Weyl fermion. Later a different type of WSM, termed type-II WSM, was predicted to break the Lorentz invariance and have no high-energy counterpart [1]. We have predicted a layered material, the orthorhombic Td phase of MoTe₂, as an ideal candidate of the type-II WSM [1]. Soon after our prediction, MoTe₂ has been verified as the first type-II WSM by several independent ARPES experiments. In this talk, I will introduce the theoretical and experimental progress in the Weyl band structure, surface Fermi arcs and spin Hall effect in the titled material.

Fermi Arc Mediated Entropy Transport in Topological Semimetals

Nandini Trivedi

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The low energy excitations of topological Weyl semimetals are comprised of linearly dispersing Weyl fermions originating at Weyl points that act as monopoles of Berry curvature in momentum space in the bulk. Furthermore, on the surface there exist topologically protected Fermi arcs at the projections of the Weyl points. We propose a novel pathway for entropy transport involving Fermi arcs on one surface connecting to Fermi arcs on the other surface via bulk states that are channeled via the Weyl monopoles. We present results for the temperature and magnetic field dependence of the magneto-thermal conductance of this conveyor belt channel. The circulating currents result in only a net entropy transport without any net charge transport. We provide results for the Fermi arc-mediated magneto-thermal conductivity in the low-field semiclassical limit as well as in the high-field ultra-quantum limit, where only chiral Landau levels are involved. Our work provides the first proposed signature of Fermi arc-mediated magneto-thermal transport and sets the stage for utilizing and manipulating the topological Fermi arcs in thermal applications.

Nernst Effect in the Weyl Semimetal NbP

Jos Heremans

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Department of Materials Science and Engineering, The Ohio State University
Department of Physics, The Ohio State University

Weyl semimetals have expanded research on topologically protected transport beyond topological insulators by adding two unique signatures: Berry monopoles in the bulk with linearly dispersing (Dirac) electronic states, and topologically robust gapless “Fermi arcs” on the surface that terminate on the projections of bulk nodes. Thermal transport measurements on Weyl fermions provide unique insight into their properties because they add entropy transport to the conventional charge transport properties like Hall effect and magnetoresistance. Here, thermoelectric and thermomagnetic experiments on single-crystal NbP are interpreted with a self-consistent theory without adjustable parameters. The Nernst thermopower at 1 T is much larger than the Seebeck thermopower, behaves like the anomalous Nernst effect, and has a pronounced maximum around $T_W = 90$ K. This is attributed to a pinning of the electrochemical potential $E_F(T)$ to the Weyl point energies at $T = T_W = E_{F0} / k_B$, where $E_{F0}$ is the chemical potential at $T=0K$, determined by the unintentional doping of the sample and/or the presence of other non-Weyl pockets in the Fermi surface. The pinning results from the charge-neutrality condition in the sample and the symmetry of the Dirac bands around the Dirac point. The temperature and field dependences of the Nernst effect result from the bipolar nature of the Weyl fermion, because the Nernst effect is an even function of the polarity of the charge carrier, unlike the Seebeck or Hall effects which are odd functions.
Wednesday 2:30-3:10 (Invited)

2D Materials for Spintronics – Graphene and Topological Insulators

Ching-Tzu Chen

IBM Thomas J. Watson Research Center

Novel two-dimensional electronic systems present unique opportunities for spintronic applications. In this seminar I will discuss two specific examples. First, we explore the potential of interfacial exchange interaction in 2D materials for spin control. Using graphene as a prototype, we demonstrate that its coupling to a model magnetic insulator (EuS) produces a substantial magnetic exchange field (> 14 T), which yields orders-of-magnitude enhancement in the spin signal originated from the Zeeman spin-Hall effect. Furthermore, the strong exchange field lifts the spin degeneracy of graphene in the quantum Hall regime, which may lead to interesting spin-polarized edge transport and thus open up new application space for classical and quantum information processing. Next we examine the potential of topological insulators as spin-source materials. Using a new spin-polarized tunneling method, giant charge-spin conversion efficiency in topological insulators is revealed, well exceeding that in conventional magnetic tunnel junctions. Through a comparative study between Bi$_2$Se$_3$ and (Bi,Sb)$_2$Te$_3$, we verify the topological-surface-state origin of the observed giant spin signals and further extract the energy dependence of the effective spin polarization in Bi$_2$Se$_3$. 
Wednesday 3:10-3:50 (Invited)

Spin Transport in hBN-Graphene-hBN van der Waals Heterostructures

Mallikarjuna Gurram

Physics of Nanodevices, Zernike Institute for Advanced Materials, University of Groningen, The Netherlands

In the first half of my talk, I will present how we use an electric-field to induce drift in the spin transport channel to guide the spin current in a high mobility graphene, encapsulated between two hBN flakes [1]. The spin relaxation length at zero drift field is 7.7 µm at room temperature and can be enhanced up to 90 µm in the presence of the drift field with a 88% guiding of the spin current. These results show the potential of carrier drift for spin-based logic operations and devices. In the second half, I will present spin transport in a fully hBN encapsulated monolayer-graphene van der Waals heterostructure, at room temperature [2]. A top-layer of bilayer-hBN is used as a tunnel barrier for spin-injection and detection in graphene with ferromagnetic cobalt electrodes. Using a bilayer hBN tunnel barrier for spin-injection into a fully hBN encapsulated graphene, we can induce spin-injection(detection) polarizations up to 70% (100%) with an applied bias across the injector(detector) contacts. With such high polarizations, we also measure a 2-terminal spin-valve signal of 800 Ohms, i.e., a magnetoresistance value of 2.7% at room temperature in graphene, which can be enhanced even up to 20% by optimizing the contact geometry. The obtained values demonstrate the potential of hBN as a tunnel barrier for future spintronics devices.


Spin Relaxation in Graphene Spin Valves: Spin Absorption and Interfacial Dephasing

Paul Crowell

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Graphene was originally anticipated to be a nearly ideal spin channel material, with weak spin-orbit and no hyperfine coupling (for $^{12}\text{C}$). Measured spin relaxation times, however, are much shorter than theoretical predictions. In this talk, I will focus on spin relaxation mechanisms that dominate in actual spintronic devices, particularly spin valves with both non-magnetic and magnetic metallic electrodes, and with and without tunnel barriers. Drawing on experience with both semiconductor and metallic spin channels, a framework for interpreting spin valve measurements in both in-plane and perpendicular magnetic fields has been developed. This approach, based on an extension of the usual Valet-Fert model, has proven to be remarkably successful for interpreting measurements on devices with tunnel barriers as well as many aspects of experiments on spin valves with “transparent” interfaces. I will discuss work at Minnesota on graphene spin valves, with spin channels prepared by chemical vapor deposition, in which this basic picture is adequate. More recently, however, an experiment being conducted at Ohio State has explored spin relaxation in graphene spin valves on which a normal metal or ferromagnetic island is deposited in situ, without an intervening tunnel barrier. This experiment allows for measurements of effective relaxation rates for FM or normal metal thicknesses ranging from the sub-monolayer regime to several nanometers. The data suggest clearly a distinct relaxation mechanism associated with the ferromagnet/graphene interface. I will discuss the implications for devices based on spin transfer torque.

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Exciton Spin Dynamics in Hybrid Organic-Inorganic Perovskites

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The hybrid organic-inorganic perovskites have emerged as a new class of semiconductors which make excellent solar cells with an efficiency over 20%. They are also highly promising semiconductors for the field of spintronics due to their large and tunable spin-orbit coupling, spin-dependent optical selection rules, and predicted electrically tunable Rashba spin splitting. I will present our latest study of exciton spin dynamics on the solution processed polycrystalline CH$_3$NH$_3$PbCl$_x$I$_{3-x}$. With time-resolved Faraday rotation (TRFR) and optical Hanle measurements, we demonstrate the optical orientation and quantum beating of excitons in the perovskites, which confirms the spin-dependent optical transitions. The energy dependence of the Faraday rotation follows the exciton absorption band at low temperatures, confirming its excitonic origin. The TRFR in zero field reveals unexpected long spin lifetimes exceeding 1 ns at 4K, given that Pb and I exhibit large spin-orbit coupling, and usually lead to fast spin relaxation. Application of a transverse magnetic field causes quantum beating at two distinct frequencies, and the approximate linear relationships give two g-factors, which we assign to electrons and holes as $g_e = 2.63$, and $g_h = -0.33$. These results provide a basic picture of the exciton states in hybrid perovskites, and suggest they hold potential for spintronic applications [1].

Room Temperature Strong Coupling Between 2D Material Excitons and 1D Photonic Crystals

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The microcavity exciton-polariton system has been a fertile ground for rich manybody physics and novel nonlinear photonic device applications. Monolayer transition-metal dichalcogenides (TMDs) are well suited for creating compact, versatile, high-temperature polariton systems for their strong exciton absorption, large binding energy, and flexibility to integrate with other 2D materials and photonic structures. TMD-polaritons have been reported in Fabry-Perot cavities and plasmonic structures, which are bulky, inflexible and/or lossy. We discuss in this talk photonic crystals (PCs) as a different platform for TMD-polaritons, which allow both high cavity quality and small mode volume. Strong-coupling was observed using a monolayer of WS2 on a 1D photonic crystal at room temperature, and up to 120 K for WSe2. The TMD-PC polariton system is a fraction of wavelength in thickness, easy to fabricate, allowing unprecedented flexibility for mode engineering and integration. Combined with the many unique properties of 2D materials and robust coherence by strong light-matter coupling, the system promises new physics and device applications.

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Tuning Spin and Valley Properties of 2D Transition Metal Dichalcogenides by Electric Fields, Magnetic Fields, and Light

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In this talk, we will review our progress in the use of external perturbations to modify the spin/valley properties of transition metal dichalcogenide monolayers. We have recently demonstrated how the use of in-plane magnetic fields can brighten spin-forbidden optical transitions of band-edge excitons in WSe$_2$. This has allowed us to directly observe dark exciton states in this material, which lie below the bright states and strongly quench light emission at low temperatures. The magnetic field further provides a means of tuning the lifetime of these states. In a different vein, in-plane electric fields are used to reveal the spin-valley Hall effect in p-type WSe$_2$ monolayers. Under conditions of current flow in the monolayer, the spin-valley Hall process acts to separate spatially in the transverse direction holes in one valley (with one spin) from those in the opposite valley (with the opposite spin). The process, previously reported at low temperatures for electrons, is quite robust for holes and has been observed at room temperature using Kerr rotation mapping. Finally, we describe how the strong light fields can be used to change the valley characteristics of an excitonic state. This is accomplished by transiently modifying the energies of one valley relative to the other through the optical Stark effect with circularly polarized light. The change in energies leads to a change in the relative phase of the components of the exciton in the two valleys. The result is a rotation of the valley exciton pseudospin. We read out the rotation of the exciton by the modified polarization of light emission from the exciton.
Besides their promise for 2D opto-electronics, monolayer transition-metal dichalcogenide (TMD) semiconductors have also revitalized longstanding interests in exploiting both the spin and valley pseudospin of electrons and holes for potential applications in (quantum) information processing. While several recent studies suggest encouragingly long timescales for spin/valley relaxation of resident electrons and holes in individual TMDs, an essential but as-yet-unanswered question concerns how these intrinsic timescales vary with carrier density, particularly when systematically tuning between electron-doped and hole-doped regimes and spin-valley locking changes dramatically. Here we measure the spin/valley dynamics of resident carriers in both n- and p-type regimes in single electrostatically-gated crystals of exfoliated monolayer WSe$_2$. Using time-resolved Kerr rotation, we observe long (~70 ns) polarization relaxation of electrons that is sensitive to in-plane magnetic fields B$_y$, indicating spin relaxation. In marked contrast, extraordinarily long (~2 microseconds) polarization relaxation of holes is revealed in the p-type regime, that is unaffected by B$_y$, directly confirming the widely-held picture of strong spin-valley locking in the valence band of monolayer TMDs. Supported by continuous-wave Kerr spectroscopy and Hanle-effect measurements, these studies provide a unified picture of carrier polarization dynamics in monolayer TMDs, which can guide design principles for future valleytronic devices.
Long-Lived Hole Spin/Valley Polarization Probed by Kerr Rotation in Monolayer WSe$_2$

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Transition metal dichalcogenide monolayers are only several atoms thick, yet several materials in this category, such as molybdenum disulfide and tungsten diselenide, are direct gap semiconductors and have conduction and valence band edges located at two inequivalent valleys (K and K’). Due to polarization-dependent optical selection rules, preferential excitation of carriers in one valley can be generated by optical pumping. However, a wide range of valley decay times have been reported, spanning several picoseconds to hundreds of nanoseconds.

Here we present results on tungsten diselenide monolayers grown by metal-organic chemical vapor deposition (MOCVD) that reveal a spin/valley lifetime of 80 ns at low temperature (10 K) [1]. By using the optical pump-probe technique of time-resolved Kerr rotation, we can measure signals that exceed the recombination time of photoexcited carriers, which would be difficult to measure using time-resolved photoluminescence due to the diminished emission over time. However, long decay times can also become challenging to measure using time-resolved Kerr rotation when they exceed the laser repetition period and delay line range. By performing additional measurements as a function of pump-probe spatial separation, we find that we are able to more accurately determine the decay time.

We also present measurements with applied transverse magnetic fields up to 300 mT. Over this range, we observe negligible change in the time-resolved Kerr rotation signal and do not observe spin precession. Wavelength-dependent Kerr rotation measurements show that the signal is largest near the free exciton emission energy, even when the photoluminescence is dominated by emission at the localized exciton energy at low temperature.

Spin-Valley Locking and Mixed Parity Pairing in Superconducting 2D NbSe₂

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2D NbSe₂ has emerged as a new non-centrosymmetric superconductor. As a result of the crystal symmetry and the strong spin-orbit interactions, electron spins in 2D NbSe₂ are locked to the out-of-plane direction (i.e. effective Ising spins), giving rise to unique magnetic properties in the superconducting state. In this talk, I will present measurements of the material’s upper critical field. It significantly exceeds the conventional spin-paramagnetic limit, in support of Cooper pairing of electrons with Ising spins. I will also discuss our recent measurements of the superconducting gap by tunneling spectroscopy under high in-plane magnetic fields. A continuous paramagnetic-limited superconductor-metal transition has been observed, which is in stark contrast to the corresponding abrupt transition in BCS superconductors. The observation provides evidence for finite spin susceptibility arisen from mixed-parity pairing in 2D NbSe₂. Our studies pave the path for the search for topological superconductivity in two-dimensional superconductors.
Optospintronics and 2D Magnets

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Two dimensional (2D) materials provide a unique platform for investigating the properties of spin and valley degrees of freedom, which can be probed by optical methods and electrical transport methods. Graphene provides an excellent medium for spin transport within a low spin orbit coupling (SOC) environment for long spin diffusion lengths at room temperature. Monolayer transition metal dichalcogenides (TMD) provide optical coupling to the spin and valley degrees of freedom within a high SOC environment. Ferromagnetic metals and insulators provide a means for electrical injection, detection, and manipulation of spin and valley degrees of freedom. One distinguishing characteristic of 2D materials is the ability to produce vertical heterostructures that combine vastly different functionalities at the length scale of a few atoms or less. Taking advantage of such an opportunity requires the use and development of advanced synthesis, fabrication, and characterization techniques for creating systems with atomic-scale precision and performing spin/valley-sensitive measurements with high fidelity. In this talk, I will present recent work on some of the first steps toward multifunctional 2D spintronics. This includes optical spin injection into graphene via optical excitation in MoS$_2$/graphene heterostructures [1], spin/valley dynamics in monolayer TMDs, and room temperature ferromagnetism in monolayer van der Waals magnets.