Research Statement

I completed my doctoral studies in theoretical condensed matter physics in December 2016 at the University of California, Riverside (UCR). Since then, I have been an instructor at Central New Mexico Community College (CNM), primarily teaching introductory physics courses, but my research interests have not subsided. In fact, my interests have grown beyond traditional disciplinary boundaries — I am widely interested in strongly interacting many-body systems of various types including: condensed matter systems with nontrivial band topology or fascinating states like those involved in Kondo screening or superconductivity, social systems where humans are interpreted as elementary constituents, as well as characterizations of those systems like magnetic, optical, and transport behaviors.

My greatest strengths, as illustrated by the following projects, are my versatility and adaptability. I am quite accustomed to approaching new and challenging areas of theoretical investigation, learning and building expertise with associated tools at every turn. Due to my broad interests, which are continually expanding further, I am considerably open-minded to various future research topics. I am very interested in researching fundamental quantum mechanics, topological materials and effects, light-matter interactions, spin systems and magnetic effects, as well as sociodynamics and other areas.

What follows are brief descriptions of each major research project I have published, along with some of the side-projects completed en route.

Weyl and line-node semimetals

University of California, Riverside; 2012-2014; with Vivek Aji (advisor)

I began graduate research in the Summer of 2012, getting an early start by participating in the GradEdge program at UCR. My knowledge of condensed matter theory was very limited at the time, but I immediately began exploring a model system hosting Weyl nodes. It involved a multilayer heterostructure with alternating topological insulators (TI) and normal insulators (NI) of equal thickness. I quickly learned about topological insulators and their nodal surface states. Those state are included in the model along with distinct hopping energies for crossing the TI and NI layers. To generate Weyl nodes, time-reversal symmetry is broken by assuming some magnetization in the NI layers (e.g. with ferromagnetic insulators), directed along the growth axis of the heterostructure. The very interesting point is that the device is tunable (e.g. controlling magnetization with temperature) and the Weyl semimetal phase appears when the magnetization surpasses a critical value.

My advisor and I considered the model with a magnetization directed in-plane rather than in the growth direction. He suggested that the axis separating Weyl nodes of opposite chirality would simply be shifted (e.g. along the k_x axis rather than k_z), but I wasn't convinced. After studying standard concepts in condensed matter, I obtained a band structure for the device which didn't show Weyl nodes at all – instead it revealed a continuous nodal curve, or "line-node". Upon convincing others of the line-node result, we found a mention of it in the literature but very little diagnostic information. Thus we decided to elucidate basic properties of the line-node phase in detail, which would be useful to decide if a particular device hosts it. I completed all of the above steps during this first summer of research work.

My research progress slowed when first-year graduate courses took priority. But I devoted available time to better understand the Weyl and line-node phases, and diagnostic calculations like transport under the Kubo formula and self-consistent Born approximation (SCBA).

When I was able to focus fully on research once more, I finished working out details of the Kubo formula and SCBA, learned about magnetic oscillations (i.e. de Haas-van Alphen), and employed Mathematica to perform calculations and generate plots for the line-node semimetal model while avoiding further approximations. These calculations were completed by the end of 2013 at which point I formalized the results for publication. I was preoccupied with second-year classes, but my advisor presented the findings at the 2014 March meeting and the manuscript was submitted shortly thereafter. The work was accepted for publication pending revisions, and was published later in 2014 in Physical Review B. Now seven years later, the journal reports 94 citations of this work, "Tunable Line Node Semimetals".

Two-dimensional and topological materials

University of California, Riverside; 2014-2017; with Vivek Aji (advisor).

In early 2014, I encountered the fascinating spin-split band structure and nontrivial topology of monolayer transition metal dichalcogenides (TMDs). The valence bands are strongly spin-split due to the strong spin-orbit coupling of the transition metal (either molybdenum or tungsten) and broken inversion symmetry. The presence of low-energy valleys about K/K' points and spin-valley locking in valence bands allow for interesting spin/valley phenomena. So, our group decided to investigate superconductivity and Kondo screening in lightly hole-doped TMDs — I volunteered for the latter task, while other group members worked on the former, and we met often to discuss details and calculations of both phenomena.

Investigating the Kondo screening cloud lead me to work on multiple side-projects. I learned about band topology, from classic work on the quantum Hall effect and adiabatic changes to more recent work like magnetic Bloch bands. I also performed analytic calculations to clarify optical selection rules for atoms with strong spin-orbit coupling, and generalized to systems like TMDs which have both spin-orbit coupling and nontrivial topology. I found other specific rules in the literature for systems with broken inversion symmetry, essentially leading to optical circular dichroism — the handedness of circularly-polarized light selects the excited valley in TMDs. I also worked out details of the Kondo problem in typical metals including approaches for quantifying the screening effects: the resistance minimum, Kondo's perturbative calculation, Green function methods, exact solutions like the Bethe ansatz, Fermi liquid and numerical renormalization group approaches, and the variational wavefunction to reveal the ground state structure.

In the context of monolayer TMDs, I initially focused on formulating an appropriate variational wavefunction. Ultimately, my goal was to determine properties of the screened state for usual hole-doped TMDs, then to extend the procedure for optically-excited TMDs where one valley (and one spin) is selectively depopulated. By the end of 2014, I had the wavefunction and variational solutions for its parameters and energy in the unexcited case, which revealed that spin fluctuations survived the screening effects ($S^2 > 0$); I presented these results in the 2015 March meeting. However, the excited case proved to be more difficult to assess and my attention was drawn to spin-Hall effects in TMDs. I learned about the spin-Hall effect in general, then performed several calculations for hole-doped TMDs using diagrammatic perturbation theory to determine the intrinsic, side-jump, and skew contributions to the spin-Hall conductivity during the Summer and Fall of 2015. Unfortunately, as I prepared to present those results at the 2016 March meeting, I came across a previous work which had already outlined those terms for the same monolayer material. Notably, my calculations included an inter-valley scattering contribution which significantly modified the spin-Hall conductivity under some specific conditions, so I proceeded to present at the meeting with emphasis on this additional term.

I did not formally publish the above spin-Hall results, since the main points were already described in the literature, but I was still very curious about Kondo screening in optically-excited TMDs. Beginning in 2016, I reworked every calculation from band structure and Anderson hybridization (including the Schrieffer-Wolff transformation) to the variational wavefunction. I determined that the variational wavefunction would not sufficiently capture the full physics of the excited case, so I decided to employ the numerical renormalization group. The well-known method had many preexisting computational tools, but none were able to capture the spin-split and spin-valley locked properties of hole-doped TMDs. So, I built my own code from scratch using Mathematica, only utilizing a package to handle second-quantization rules. I spent the bulk of 2016 generalizing the numerical renormalization procedure for optically-excited TMDs and writing code to properly calculate spin, entropy, magnetic susceptibility, and spin-resolved spectral functions. While the computer evaluated my code, I worked on drafts of the manuscript and wrote my doctoral dissertation. By December 2016, I completed my dissertation and final defense, and submitted the final draft of the paper, "Kondo screening in two-dimensional *p*-type transition-metal dichalcogenides", to Physical Review B. The paper was officially published in Physical Review B two months later, in February 2017, following minor revisions.

Social interaction and macroscopic behavior

Central New Mexico Community College; 2017-2020; independently.

My interest in applications of many-body interactions outside of physics began during my graduate education. I had some time in 2017 between my final defense and my new role as an instructor at CNM, so I began to search through books and other literature to familiarize myself with extensions of physical equations to other areas. I came across many works, most notably from Haken and Weidlich, which suggested the master equation as the most general framework, applicable within: physics, chemistry, biology, sociology, economics, and many other areas. I hadn't known it by that name, but I had actually employed the master equation previously in physics, in the context of Boltzmann equations used in transport calculations, and in detailing the quasi-equilibrium optically-excited state in monolayer TMDs resulting from exposure to a steady source of light.

I studied the master equation deeply, along with its continuum counterpart (Fokker-Planck), working out example problems like the basic laser model. Simultaneously, I found big claims from parasitologists about macroscopic social behavior based on effects of parasites in individual organisms (including humans). I was quite skeptical that entire societies may be controlled by parasitic influences, and I had the tools to study exactly how changes to elementary constituents affect system-wide outcomes, so I set to work. I referred to a general framework for sociodynamics (Helbing) to properly account for individual opinions, behaviors, and effects of social interaction. I then formulated an appropriate analytical model of social behavior in the presence of a parasitically-influenced subpopulation. I worked out all social transitions in that context, took the thermodynamic limit leading to the corresponding Fokker-Planck equation, and developed nonlinear mean-field equations for the resultant macroscopic social behavior.

Aside from teaching and other responsibilities, I spent much of 2018 writing Python code with my own class definitions to solve the nonlinear differential equations from my model. Because opinions and parasitic influences are often cyclical, I extended the code to investigate hysteresis effects in the model. It was a slow-going part-time project that I pursued without funding or collaboration, but by the end of 2018 I had generated solutions, bifurcation and phase diagrams, and hysteresis loops for a range of model parameters. An interesting result emerged wherein mean social behavior could actually be controlled by the presence of an infected minority, so I spent some time in 2019 preparing a formal manuscript. I submitted the work to Springer's Journal of Statistical Physics in November 2019, and it was later accepted pending minor revisions. The paper, "Hysteresis Effects in Social Behavior with Parasitic Infection", was finally published in June 2020.

Summary

My greatest strengths, as illustrated by the above projects, are my versatility and adaptability. I am quite accustomed to approaching new and challenging areas of theoretical investigation, learning and building expertise with associated tools at every turn. Due to my broad interests, which are continually expanding further, I am considerably open-minded to various future research topics. I am very interested in researching fundamental quantum mechanics, topological materials and effects, light-matter interactions, spin systems and magnetic effects, as well as sociodynamics and other areas.