

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 19-05-2021	2. REPORT TYPE Final Report	3. DATES COVERED (From - To) 7-May-2016 - 6-May-2021
---	--------------------------------	---

4. TITLE AND SUBTITLE Final Report: Chiral Spin Liquids and Other Topological Phases of Cold Atoms and Molecules in Optical Lattices (6.3.1)	5a. CONTRACT NUMBER W911NF-16-1-0182
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 611102

6. AUTHORS	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES Virginia Polytechnic Institute & State Unive North End Center, Suite 4200 300 Turner Street, NW Blacksburg, VA 24061 -0001	8. PERFORMING ORGANIZATION REPORT NUMBER
---	--

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSOR/MONITOR'S ACRONYM(S) ARO
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 68316-PH.43

12. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.
--

13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Vito Scarola
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 540-231-8757

RPPR Final Report
as of 20-May-2021

Agency Code: 21XD

Proposal Number: 68316PH

Agreement Number: W911NF-16-1-0182

INVESTIGATOR(S):

Name: Vito W. Scarola
Email: scarola@vt.edu
Phone Number: 5402318757
Principal: Y

Name: Sumanta Tewari
Email: stewari@clemson.edu
Phone Number: 8643537172
Principal: N

Organization: **Virginia Polytechnic Institute & State University**

Address: North End Center, Suite 4200, Blacksburg, VA 240610001

Country: USA

DUNS Number: 003137015

EIN: 546001805

Report Date: 06-Aug-2021

Date Received: 19-May-2021

Final Report for Period Beginning 07-May-2016 and Ending 06-May-2021

Title: Chiral Spin Liquids and Other Topological Phases of Cold Atoms and Molecules in Optical Lattices (6.3.1)

Begin Performance Period: 07-May-2016

End Performance Period: 06-May-2021

Report Term: 0-Other

Submitted By: Vito Scarola

Email: scarola@vt.edu

Phone: (540) 231-8757

Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 9

STEM Participants: 11

Major Goals: See Attached

Accomplishments: See Attached

Training Opportunities: See Attached

Results Dissemination: See Attached

Honors and Awards: See Attached

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI

Participant: Vito Scarola

Person Months Worked: 1.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Co PD/PI

Participant: Sumanta Tewari

Person Months Worked: 2.00

Funding Support:

RPPR Final Report
as of 20-May-2021

Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Zhangjie Qin
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Woo-Ram Lee
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Junhua Zhang
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Peter Raum
Person Months Worked: 11.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Hoi Hui
Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Mengsu Chen
Person Months Worked: 9.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Mi Yan
Person Months Worked: 11.00 **Funding Support:**
Project Contribution:
National Academy Member: N

RPPR Final Report as of 20-May-2021

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Phys. Rev. B

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevB.97.035114

Volume: 97

Issue:

First Page #: 035114

Date Submitted: 8/20/18 12:00AM

Date Published: 1/9/19 10:00AM

Publication Location:

Article Title: Quantum anomalous Hall state from spatially decaying interactions on the decorated honeycomb lattice

Authors: Mengsu Chen, Hoi-Yin Hui, Sumanta Tewari, V. W. Scarola

Keywords: Strongly correlated Lattice models

Abstract: Topological phases typically encode topology at the level of the single particle band structure. But a remarkable new class of models shows that quantum anomalous Hall effects can be driven exclusively by interactions, while the parent non-interacting band structure is topologically trivial. Unfortunately, these models have so far relied on interactions that do not spatially decay and are therefore unphysical. We study a model of spinless fermions on a decorated honeycomb lattice. Using complementary methods, mean-field theory and exact diagonalization, we find a robust quantum anomalous Hall phase arising from spatially decaying interactions. Our finding paves the way for observing the quantum anomalous Hall effect driven entirely by interactions.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Phys. Rev. B

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevB.97.195153

Volume: 97

Issue:

First Page #: 195153

Date Submitted: 8/20/18 12:00AM

Date Published: 5/29/18 4:00AM

Publication Location:

Article Title: Suppression of Hall number due to charge density wave order in high-Tc cuprates

Authors: Girish Sharma, S. Nandy, A. Taraphder, Sumanta Tewari

Keywords: Strongly Correlated

Abstract: Understanding the pseudogap phase in hole-doped high temperature cuprate superconductors remains a central challenge in condensed matter physics. From a host of recent experiments there is now compelling evidence of translational symmetry breaking charge density wave (CDW) order in a wide range of doping inside this phase. Two distinct types of incommensurate charge order -- bidirectional at zero or low magnetic fields and unidirectional at high magnetic fields close to the upper critical field H_{c2} -- have been reported so far in approximately the same doping range between $p \approx 0.08$ and $p \approx 0.16$. In concurrent developments, recent high field Hall experiments have also revealed two indirect but striking signatures of Fermi surface reconstruction in the pseudogap phase, namely, a sign change of the Hall coefficient to negative values at low temperatures at intermediate range of hole doping and a rapid suppression of the positive Hall number without change in sign near optimal doping.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

RPPR Final Report as of 20-May-2021

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.118.115302
Volume: 118 Issue: 11 First Page #:
Date Submitted: 8/25/17 12:00AM Date Published: 3/1/17 5:00AM
Publication Location:
Article Title: Thermometry for Laughlin States of Ultracold Atoms
Authors: P. T. Raum, V. W. Scarola
Keywords: Atomic, Molecular & Optical
Abstract: Cooling atomic gases into strongly correlated quantum phases requires estimates of the entropy to perform thermometry and establish viability. We construct an ansatz partition function for models of Laughlin states of atomic gases by combining high temperature series expansions with exact diagonalization. Using the ansatz we find that entropies required to observe Laughlin correlations with bosonic gases are within reach of current cooling capabilities.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevA.95.053624
Volume: 95 Issue: 5 First Page #:
Date Submitted: 8/25/17 12:00AM Date Published: 5/1/17 4:00AM
Publication Location:
Article Title: Dynamics of disordered states in the Bose-Hubbard model with confinement
Authors: Mi Yan, Hoi-Yin Hui, V. W. Scarola
Keywords: Atomic, Molecular & Optical
Abstract: Observations of center-of-mass dynamics offer a straightforward method to identify strongly interacting quantum phases of atoms placed in optical lattices. We theoretically study the dynamics of states derived from the disordered Bose-Hubbard model in a trapping potential. We find that the edge states in the trap allow center-of-mass motion even with insulating states in the center. We identify short- and long-time-scale mechanisms for edge-state transport in insulating phases. We also argue that the center-of-mass velocity can aid in identifying a Bose-glass phase. Our zero-temperature results offer important insights into mechanisms of transport of atoms in trapped optical lattices while putting bounds on center-of-mass dynamics expected at nonzero temperature.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevA.95.033603
Volume: 95 Issue: 3 First Page #:
Date Submitted: 8/25/17 12:00AM Date Published: 3/1/17 5:00AM
Publication Location:
Article Title: Superfluidity in the absence of kinetics in spin-orbit-coupled optical lattices
Authors: Hoi-Yin Hui, Yongping Zhang, Chuanwei Zhang, V. W. Scarola
Keywords: Atomic, Molecular & Optical
Abstract: At low temperatures bosons typically condense to minimize their single-particle kinetic energy while interactions stabilize superfluidity. Optical lattices with artificial spin-orbit coupling challenge this paradigm, because here kinetic energy can be quenched in an extreme regime where the single-particle band flattens. To probe the fate of superfluidity in the absence of kinetics we construct and numerically solve interaction-only tight-binding models in flatbands. We find that superfluid states arise entirely from interactions operating in quenched kinetic energy bands, thus revealing a distinct and unexpected condensation mechanism. Our results have important implications for the identification of quantum condensed phases of ultracold bosons beyond conventional paradigms.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: Y

RPPR Final Report

as of 20-May-2021

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review A

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevA.94.043601

Volume: 94

Issue: 4

First Page #:

Date Submitted: 8/25/17 12:00AM

Date Published: 10/1/16 4:00AM

Publication Location:

Article Title: Stability of emergent kinetics in optical lattices with artificial spin-orbit coupling

Authors: Mengsu Chen, V. W. Scarola

Keywords: Atomic, Molecular & Optical

Abstract: Artificial spin-orbit coupling in optical lattices can be engineered to tune band structure into extreme regimes where the single-particle band flattens leaving only interparticle interactions to define many-body states of matter. Lin et al. [F. Lin, C. Zhang, and V. W. Scarola, Phys. Rev. Lett. 112, 110404 (2014)] showed that under such conditions interactions lead to a Wigner crystal of fermionic atoms under approximate conditions: no bandwidth or band mixing. The excitations were shown to possess emergent kinetics with fractionalized charge derived entirely from interactions. In this work we use numerical exact diagonalization to study a more realistic model with nonzero bandwidth and band mixing. We map out the stability phase diagram of the Wigner crystal. We find that emergent properties of the Wigner crystal excitations remain stable for realistic experimental parameters. Our results validate the approximations made by Lin et al..

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review B

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevB.94.125149

Volume: 94

Issue: 12

First Page #:

Date Submitted: 8/25/17 12:00AM

Date Published: 9/1/16 4:00AM

Publication Location:

Article Title: Fast and efficient stochastic optimization for analytic continuation

Authors: F. Bao, Y. Tang, M. Summers, G. Zhang, C. Webster, V. Scarola, T. A. Maier

Keywords: Numerical Techniques

Abstract: The analytic continuation of imaginary-time quantum Monte Carlo data to extract real-frequency spectra remains a key problem in connecting theory with experiment. Here we present a fast and efficient stochastic optimization method (FESOM) as a more accessible variant of the stochastic optimization method introduced by Mishchenko et al. [Phys. Rev. B 62, 6317 (2000)], and we benchmark the resulting spectra with those obtained by the standard maximum entropy method for three representative test cases, including data taken from studies of the two-dimensional Hubbard model. We generally find that our FESOM approach yields spectra similar to the maximum entropy results. In particular, while the maximum entropy method yields superior results when the quality of the data is strong, we find that FESOM is able to resolve fine structure with more detail when the quality of the data is poor. In addition, because of its stochastic nature, the method provides detailed information on the frequency-d

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

RPPR Final Report as of 20-May-2021

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review B

Publication Identifier Type:

Publication Identifier: 10.1103/PhysRevB.99.094523

Volume: 99

Issue:

First Page #: 094523

Date Submitted: 8/26/19 12:00AM

Date Published: 3/29/19 4:00AM

Publication Location:

Article Title: Kitaev chain with a quantum dot

Authors: Kitaev chain with a quantum dot Chuanchang Zeng, Christopher Moore, Apparao M. Rao, Tudor D. Star

Keywords: Topological States of Matter

Abstract: We solve analytically the problem of a finite length Kitaev chain coupled to a quantum dot (QD), which extends the standard Kitaev chain problem making it more closely related to the quantum dot-semiconductor-superconductor (QD-SM-SC) nanowire heterostructure that is currently under intense investigation for possible occurrence of Majorana zero modes (MZMs). Our analytical solution reveals the emergence of a robust Andreev bound state (ABSs) localized in the quantum dot region as the generic lowest energy solution in the topologically trivial phase. By contrast, in the bare Kitaev chain problem such a solution does not exist. The robustness of the ABS in the topologically trivial phase is due to a partial decoupling of the component Majorana bound states (MBSs) over the length of the dot potential. As a result, the signatures of the ABS in measurements that couple locally to the quantum dot, e.g., tunneling measurements, are identical to the signatures of topologically-protected MZMs.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review B

Publication Identifier Type:

Publication Identifier: 10.1103/PhysRevB.98.155314

Volume: 98

Issue:

First Page #: 155314

Date Submitted: 8/26/19 12:00AM

Date Published: 10/19/18 4:00AM

Publication Location:

Article Title: Quantized zero bias conductance plateau in semiconductor-superconductor heterostructures without non-Abelian Majorana zero modes

Authors: Christopher Moore, Chuanchang Zeng, T. D. Stanescu, Sumanta Tewari

Keywords: Topological States of Matter

Abstract: We show that partially separated Andreev bound states (ps-ABSs), comprised of pairs of overlapping Majorana bound states (MBSs) emerging in quantum dot-semiconductor-superconductor heterostructures, produce robust zero bias conductance plateaus in end-of-wire charge tunneling experiments. These plateaus remain quantized at $2e^2/h$ over large ranges of experimental control parameters. In light of recent experiments reporting the observation of robust $2e^2/h$ -quantized conductance plateaus in local charge tunneling experiments, we perform extensive numerical calculations to explicitly show that such quantized conductance plateaus, which are obtained by varying control parameters such as the tunnel barrier height, the super gate potential, and the applied magnetic field, can arise as a result of the existence of ps-ABSs.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

RPPR Final Report as of 20-May-2021

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: PHYSICAL REVIEW RESEARCH

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevResearch.2.032066

Volume: 2

Issue:

First Page #: 032066

Date Submitted: 5/17/21 12:00AM

Date Published: 9/9/19 8:00PM

Publication Location:

Article Title: Fundamental relations for anomalous thermoelectric transport coefficients in the nonlinear regime

Authors: C. Zeng, S. Nandy, S. Tewari

Keywords: Hall effect, topological matter

Abstract: Topological Weyl semimetals (WSMs) have been predicted to be excellent candidates for detecting Berry curvature dipole (BCD) and the related non-linear effects in electronics and optics due to the large Berry curvature concentrated around the Weyl nodes. And yet, linearized models of isolated tilted Weyl cones only realize a diagonal non-zero BCD tensor which sum to zero in the model of WSM with multiple Weyl nodes in the presence of mirror symmetry. On the other hand, recent ab initio work has found that realistic WSMs like TaAs-type or MoTe₂-type compounds, which have mirror symmetry, indeed show an off-diagonal BCD tensor with an enhanced magnitude for its non-zero components. So far, there is a lack of theoretical work addressing this contradiction for 3D WSMs. In this paper, we systematically study the BCD in 3D WSMs using lattice Weyl Hamiltonians, which go beyond the linearized models.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: PHYSICAL REVIEW B

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevB.102.205101

Volume: 102

Issue:

First Page #: 205101

Date Submitted: 5/17/21 12:00AM

Date Published: 4/27/20 12:00PM

Publication Location:

Article Title: Feasibility of measurement-based braiding in the quasi-Majorana regime of semiconductor-superconductor heterostructures

Authors: Chuanchang Zeng, Girish Sharma, Tudor D. Stanescu, and Sumanta Tewari

Keywords: Topological matter, quantum computing, Majorana

Abstract: The manifestation of chiral anomaly in Weyl semimetals typically relies on the observation of longitudinal magnetoconductance (LMC) along with the planar Hall effect, with a specific magnetic field and angle dependence. Here we solve the Boltzmann equation in the semiclassical regime for a prototype of a Weyl semimetal, allowing for both intravalley and intervalley scattering, along with including effects from the orbital magnetic moment (OMM), in a geometry where the electric and magnetic fields are not necessarily parallel to each other. We construct the phase diagram in the relevant parameter space that describes the shift from positive to negative LMC in the presence of OMM and sufficiently strong intervalley scattering, as has been recently pointed out for only parallel electric and magnetic fields.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

RPPR Final Report

as of 20-May-2021

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 4-Under Review
Journal: arXiv
Publication Identifier Type: Other **Publication Identifier:** rxiv:2009.05043
Volume: **Issue:** **First Page #:**
Date Submitted: 5/17/21 12:00AM **Date Published:**
Publication Location:

Article Title: Berry curvature dipole in topological Weyl semimetals

Authors: Chuanchang Zeng, Snehasish Nandy, and Sumanta Tewar

Keywords: Berry curvature, topological

Abstract: Topological Weyl semimetals (WSMs) have been predicted to be excellent candidates for detecting Berry curvature dipole (BCD) and the related non-linear effects in electronics and optics due to the large Berry curvature concentrated around the Weyl nodes. And yet, linearized models of isolated tilted Weyl cones only realize a diagonal non-zero BCD tensor which sum to zero in the model of WSM with multiple Weyl nodes in the presence of mirror symmetry. On the other hand, recent ab initio work has found that realistic WSMs like TaAs-type or MoTe₂-type compounds, which have mirror symmetry, indeed show an off-diagonal BCD tensor with an enhanced magnitude for its non-zero components. So far, there is a lack of theoretical work addressing this contradiction for 3D WSMs. In this paper, we systematically study the BCD in 3D WSMs using lattice Weyl Hamiltonians, which go beyond the linearized models.

Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: Y

DISSERTATIONS:

Publication Type: Thesis or Dissertation

Institution: Clemson University

Date Received: 25-Aug-2017

Completion Date: 8/25/16 6:01PM

Title: Topological Phenomena in Metals and Superconductors

Authors: Girish Sharma

Acknowledged Federal Support: N

Publication Type: Thesis or Dissertation

Institution: Virginia Tech

Date Received: 26-Aug-2019

Completion Date: 12/16/18 2:05AM

Title: Exact diagonalization study of strongly correlated topological quantum states

Authors: Mengsu Chen

Acknowledged Federal Support: N

Publication Type: Thesis or Dissertation

Institution: Virginia Tech

Date Received: 26-Aug-2019

Completion Date: 12/15/18 9:05PM

Title: Exact diagonalization study of strongly correlated topological quantum states

Authors: Mengsu Chen

Acknowledged Federal Support: N

Publication Type: Thesis or Dissertation

Institution: Virginia Tech

Date Received: 26-Aug-2019

Completion Date: 12/15/18 5:00AM

Title: Quantum Dynamics of Strongly-Interacting Bosons in Optical Lattices with Disorder

Authors: Mi Yan

Acknowledged Federal Support: Y

RPPR Final Report
as of 20-May-2021

Partners

,

See Attached.

I certify that the information in the report is complete and accurate:

Signature: Vito Scarola

Signature Date: 5/19/21 8:03PM

FINAL REPORT

ARO Award Number:

W911NF1610182

Prepared by:

Prof. Vito W. Scarola

scarola@vt.edu

**Department of Physics, Virginia Tech
Blacksburg, VA 24061**

Prof. Sumanta Tewari

stewari@g.clemson.edu

**Department of Physics and Astronomy, Clemson University
Clemson, SC 29634**

Program Officer:

Dr. Paul Baker

paul.m.baker4.civ@mail.mil

Army Research Office

800 Park Offices Drive

Durham, NC 27709

TABLE OF CONTENTS

Section	Page
1.0 Major Goals	3
2.0 Accomplished Under Goals	6
3.0 Training Opportunities	15
4.0 Results and Dissemination.....	16
5.0 Honors and Awards.....	22
6.0 Other Collaborators.....	23

1.0 Major Goals

Topologically ordered many-body states of matter do not necessarily display conventional order, e.g., ferromagnetism, but they carry their own unique properties such as fractionalized excitations and chiral edge currents, properties that are intimately connected to the topology of the underlying state and manifest in quantized Hall effects. One seminal example is the chiral spin liquid. The chiral spin liquid was proposed as an analogue of the Laughlin state but for spins in a frustrated lattice. It is gapped in the bulk but displays gapless excitations at the edge. The edge excitations should manifest as quantized chiral spin currents in direct analogy to chiral charge currents of Laughlin states. The Laughlin and chiral spin liquid states are also connected mathematically. Our work seeks to model ultracold atoms and molecules as routes to realizing topological phases of matter. We aim to study topological phases and their observable properties; related examples include: Chiral spin liquids, topological Mott insulators, Laughlin states, Weyl semimetals, and quantum anomalous Hall states. These states share a connection and are proposed to be realized with ultracold atoms and in solids. Key to their identification is the understanding of their chiral properties.

The following summarizes some of the major goals as individual projects:

We will use a new formalism (combining exact diagonalization and mean field theory we developed) to propose optical lattice experiments hosting topological phases. In one such study we will examine the possibility of using dipoles in a kagome optical lattice to realize a topological Mott insulator. Our preliminary estimates indicate that current technology allows the placement of dipoles in kagome optical lattice to realize this exciting new phase. We will estimate parameter regimes needed to observe the chiral edge modes characterizing this phase.

In another work we will build on our theme of studying frustration in optical lattices to realize topological phases. We will work with Brian DeMarco's experimental group at the University of Illinois Urbana-Champaign to study implementation of new interaction terms in optical lattices. We will work to show that density assisted tunneling can be used to mimic the role of long-range interactions and therefore frustration in optical lattices. We will study the use of Raman beams to implement interactions terms that can be used as a starting point for realizing topological phases.

In another work we will investigate the possibility of a current density wave phase on the checkerboard lattice for generic chemical potentials using dipolar fermions with hopping and interaction terms. The current density wave phase on the checkerboard lattice is nothing but the quantum anomalous Hall (QAH) phase, as the diagonal hopping terms are modulated right at the lattice level, which in effect gives us the $d_{xy} + id_x^2 - y^2$ phase on the square lattice, which is the QAH phase. The corresponding triplet variety is the quantum anomalous spin Hall phase. To the best of our knowledge, we are not aware of an intrinsic reason why the current density wave phase (the analog of which in the cuprates is the d-density wave (DDW) phase) is realizable by interactions only when the underlying non-interacting Fermi surface is point-like. And yet this is the only case that has been considered in the optical lattice literature so far, the difficulty of fine-tuning the chemical potential notwithstanding. We will study if the current density wave phase is realizable on checkerboard lattice for generic chemical potentials, increasing the likelihood of its realization in optical lattice systems.

We will propose a method to realize a chiral spin liquid and a related topological phase in optical lattices. We will build on the methods constructed in our group to show that synthetic fields applied to fermions in an optical lattice will allow implementation of an effective flux. This effective flux will lead to a chiral three spin term. We will show that the three-spin term can lead to topological phases: a chiral spin liquid or another new phase, a nodal line fermion phase. This latter phase is a newly discovered gapless topological phase. It is defined by a unique pattern of three intersecting nodal lines. In another work we will explore the possibility of fractionalization in flat kagome bands. Our earlier work found a chiral phase induced by the dipolar interaction in a kagome optical lattice. We will build on that work to show that placing more particle in the otherwise empty flat band will lead to a fractionalized phase. We believe that fractionally filled phase will form a uniform liquid that is chiral and is therefore adiabatically connected to the chiral spin liquid. We will explore two additional routes to novel phases of matter. These include strongly correlated bosons in optical lattices manipulated into cluster states. Cluster states are symmetry protected topological phases which also serve as resources for measurement-based quantum computing. We will look at the possibility of building cluster states and using them to realize topological properties.

We will also explore the possibility of realizing interaction induced Abelian and non-Abelian topological superfluid phases in cold atom systems. These will be studies similar to our earlier studies of topological Mott insulators, wherein we explored the possibility of realizing non-trivial topological effects purely driven by interactions, starting from simple topologically trivial lattice Hamiltonians which may be easier to realize in cold atoms. We will focus on Kagome and checkerboard lattices known to support quadratic band touching points, which may be good non-interacting starting points to build on topological effects driven by interactions.

We will explore the possibility of topological degeneracy in strictly one-dimensional systems of cold fermions with spin-orbit coupling, Zeeman field, and an attractive onsite interactions inducing superfluid correlations. Because of strong phase fluctuations such a system is not expected to order into a superfluid even at zero temperature. Despite this, a form of two-fold topological degeneracy (gap exponentially decaying with the length of the chain) may persist in the presence of an externally imposed parabolic potential present in optical lattice systems. Such an exponential degeneracy will be critical for topological memory and quantum computation applications. We will explore this possibility using density matrix renormalization group techniques for 1D systems.

We will also investigate the realization of chiral density wave phases using degenerate fermions on 2D honeycomb lattice. Two types of phases with both valleys of the honeycomb lattice having same and opposite chirality will be investigated. We will study a spin-half fermion Hubbard model on the 2D honeycomb lattice in the framework of renormalized mean field theory for the corresponding t-J model derived in the limit of $U \rightarrow t$. The six-fold symmetric honeycomb lattice offers crystal structure in which the certain symmetries belong to the same irreducible representation. This means that if the Hamiltonian supports $d_{x^2-y^2}$ -wave order parameter on hexagonal lattice it will support the d_{xy} solutions as well with the same transition temperature, and hence a chiral density wave. At half filling this phase is a gapped insulator with local currents alternating in neighboring plaquettes, having some family resemblance to the plaquette Mott insulator phases. Apart from optimizing the optical lattice parameters, the

strength of the chiral bond currents in the chiral density wave and the analogous superfluid phases will be estimated to help identify these phases in experiments.

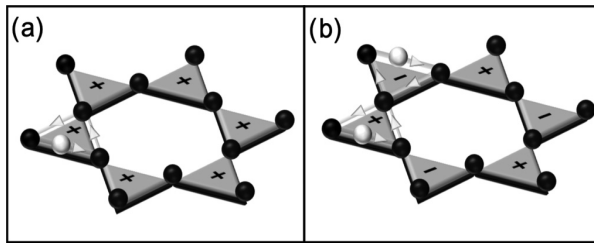
We will also consider the Harper-Hofstadter model on the square lattice and the Haldane model on the honeycomb lattice for fermions and bosons in the presence of local repulsive interactions. In the last reporting period, we considered the time-reversal-invariant spin-half version of the Harper-Hofstadter fermion model with attractive interactions modelled by the negative- U Harper-Hofstadter-Hubbard model. In the presence of a domain wall created by a dark soliton this model admitted Majorana corner modes and higher order topological superfluidity. In the next reporting period, however, we will consider spinless fermions with broken time reversal symmetry (due to the complex hopping amplitude in the Harper-Hofstadter and Haldane models) in the presence of repulsive local interactions. In the interaction dominated regime we expect the emergence of the plaquette Mott insulator phase with non-zero plaquette currents which can be probed in experiments. We expect this phase to be a relatively straightforward strongly correlated phase to access experimentally as synthetic magnetic fields are turned on, since Mott states with relatively low entropy have already been observed.

2.0 Accomplished Under Goals

Our work focused on models of atoms and molecules in frustrated optical lattices and topological states. To test viability, we estimated the entropies at which particles must be cooled to allow interesting topological phases to thermalize in optical lattices. We found that relevant energy scales are set by the strength of the interaction, which can be quite large and therefore offer promise in realizing these states at experimentally relevant entropies. In addition, we found that significant cooling can be expected in atomic gas microscope setups that are currently being constructed to host low entropy states. We also identified and studied observable chiral properties of these phases to allow experiments to identify topological order. The following shows research highlights where we modelled topological states with the long-term goal of fostering the realization of chiral topological phases in with ultracold atom experiments.

2.1 Flux-driven quantum spin liquids in kagome optical lattices, Hoi-Yin Hui, Mengsu Chen, Sumanta Tewari, and V. W. Scarola *Phys. Rev. A* 100, 053614 (2019)

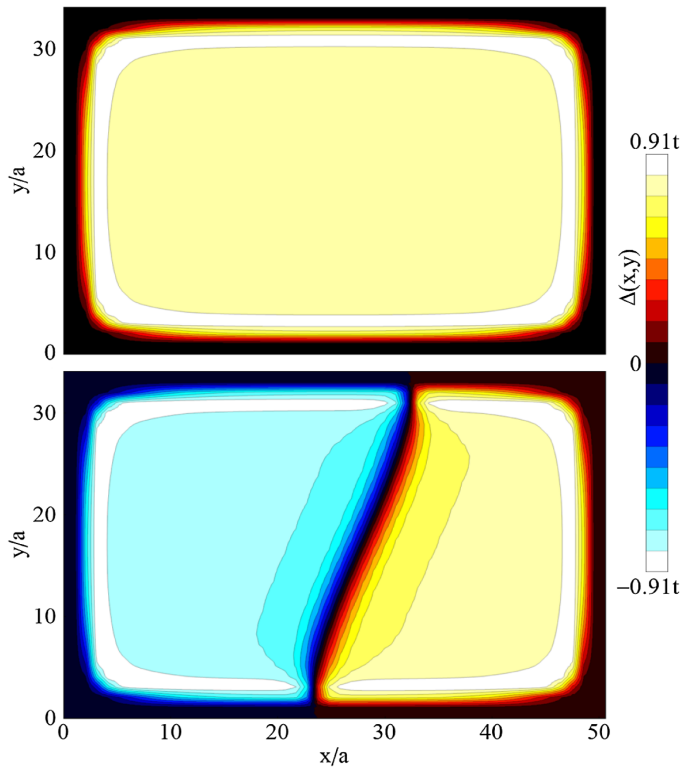
Quantum spin liquids (QSLs) define an exotic class of quantum ground states where spins are disordered down to zero temperature. We propose routes to QSLs in kagome optical lattices using applied flux. An optical flux lattice can be applied to induce a uniform flux and chiral three-spin interactions that drive the formation of a gapped chiral spin liquid. A different approach based on recent experiments using laser-assisted tunneling and lattice tilt implements a staggered flux pattern which can drive a gapless spin liquid with symmetry protected nodal lines. Our proposals, therefore, establish kagome optical lattices with effective flux as a powerful platform for exploration of QSLs.



Schematic of one fermion per site (black spheres) on a kagome lattice. The white spheres denote virtual current driven by flux passing through the lattice. The plus and minus signs denote the sign of the flux captured by the virtual currents. Panels (a) and (b) show a uniform (staggered) flux pattern. In the Heisenberg limit of a Hubbard model, virtual currents encircling flux lead to chiral three-spin terms that drive spin liquids.

2.2 Majorana Corner Modes with Solitons in an Attractive Hubbard-Hofstadter Model of Cold Atom Optical Lattices, Chuanchang Zeng, T. D. Stanescu, Chuanwei Zhang, V. W. Scarola, and Sumanta Tewari, Phys. Rev. Lett. 123, 060402 (2019).

Higher-order topological superconductors hosting Majorana-Kramers pairs as corner modes have recently been proposed in a two-dimensional quantum spin Hall insulator proximity-coupled to unconventional cuprate or iron-based superconductors. Here, we show that such MKPs can be realized using a conventional s-wave superfluid with a soliton in cold atom systems governed by the Hubbard-Hofstadter model. The MKPs emerge in the presence of interaction at the “corners” defined by the intersections of line solitons and the one-dimensional edges of the system. Our scheme is based on the recently realized cold atom Hubbard-Hofstadter lattice and will pave the way for observing possible higher-order topological superfluidity with conventional s-wave superfluids or superconductors.



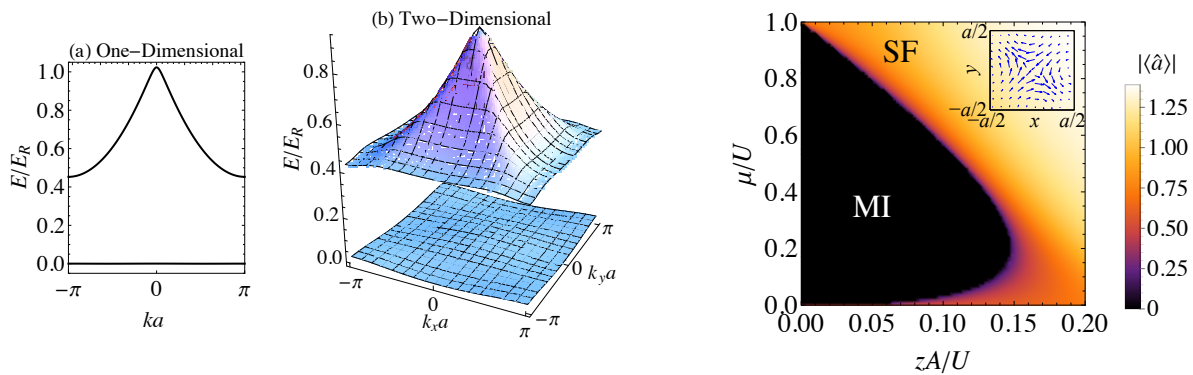
Top: Plot of the superfluid order parameter D in a rectangular geometry without a soliton.

Bottom: The same but with a soliton induced by an external laser.

Majorana corner modes were found to exist where the soliton intersects with the edge.

2.3 Superfluidity in the absence of kinetics in spin-orbit-coupled optical lattices. Hui, H. Y., Zhang, Y., Zhang, C., & Scarola, V. W. *Physical Review A*, 95(3), 33603 (2017).

At low temperatures bosons typically condense to minimize their single-particle kinetic energy while interactions stabilize superfluidity. Optical lattices with artificial spin-orbit coupling challenge this paradigm because here kinetic energy can be quenched in an extreme regime where the single-particle band flattens. To probe the fate of superfluidity in the absence of kinetics we construct and numerically solve interaction-only tight-binding models in flat bands. We find that novel superfluid states arise entirely from interactions operating in quenched kinetic energy bands, thus revealing a distinct and unexpected condensation mechanism. Our results have important implications for the identification of quantum condensed phases of ultracold bosons beyond conventional paradigms

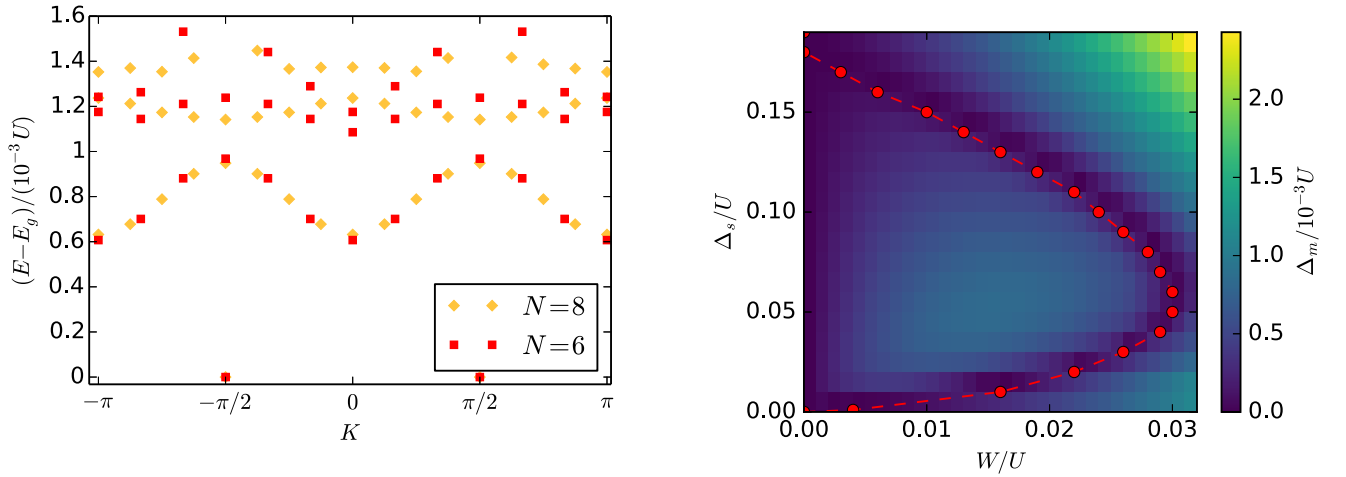


Left: Single particle energy versus wave vector for the lowest two energy bands of (a) the one-dimensional model and (b) the two-dimensional model of spin-orbit coupled atoms in optical lattices. Flat bands are found at low energies.

Right: The magnitude of the superfluid order parameter against chemical potential and effective tunneling obtained from mean field theory. The superfluid (SF) and Mott insulator (MI) derive entirely from interactions. The inset shows the spin texture in a unit cell for the 2D system.

2.4 Superfluidity in the absence of kinetics in spin-orbit-coupled optical lattices. Hui, H. Y., Zhang, Y., Zhang, C., & Scarola, V. W. *Physical Review A*, 95(3), 33603 (2017).

Artificial spin-orbit coupling in optical lattices can be engineered to tune band structure into extreme regimes where the single-particle band flattens leaving only inter-particle interactions to define many-body states of matter. Lin et al. [Phys. Rev. Lett 112, 110404 (2014)] showed that under such conditions interactions lead to a Wigner crystal of fermionic atoms under approximate conditions: no bandwidth or band mixing. The excitations were shown to possess emergent kinetics with fractionalized charge derived entirely from interactions. In this work we use numerical exact diagonalization to study a more realistic model with non-zero bandwidth and band mixing. We map out the stability phase diagram of the Wigner crystal. We find that emergent properties of the Wigner crystal excitations remain stable for realistic experimental parameters. Our results validate the approximations made by Lin et al. and define parameter regimes where strong interaction effects generate emergent kinetics in optical lattices.

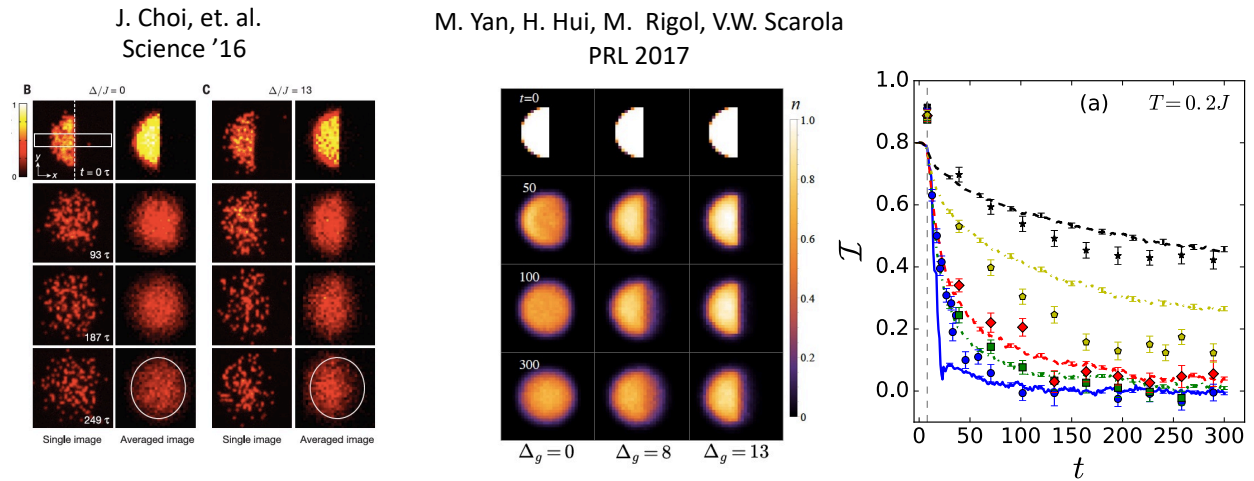


Left: Many-body energies versus total wavevector obtained from diagonalization. The gap shows stability of a Wigner crystal. The dispersive excitation shows emergent kinetics. The data collapse shows that the ground and first excited states are already in the thermodynamic limit.

Right: Stability phase diagram of the Wigner crystal with emergent kinetics plotted as function of both the single-particle band gap and the bandwidth. The color coding plots the size of the many-body gap obtained from diagonalization. The circles plot the points where the many-body gap vanishes and the line is a guide to the eye. The Wigner crystal is stable within the lobe. Outside the lobe we have a conventional Luttinger liquid with a gap set by finite-size effects.

2.5 Equilibration Dynamics of Strongly Interacting Bosons in 2D Lattices with Disorder. Yan, M., Hui, H.-Y., Rigol, M., & Scarola, V. W. *Physical Review Letters*, 119 073002 (2017).

Motivated by recent optical lattice experiments in Immanuel Bloch's group [Choi et al., *Science* 352, 1547 (2016)], we study the dynamics of strongly interacting bosons in the presence of disorder in two dimensions. We show that Gutzwiller mean-field theory (GMFT) captures the main experimental observations, which are a result of the competition between disorder and interactions. Our findings highlight the difficulty in distinguishing glassy dynamics, which can be captured by GMFT, and many-body localization, which cannot be captured by GMFT, and indicate the need for further experimental studies of this system.



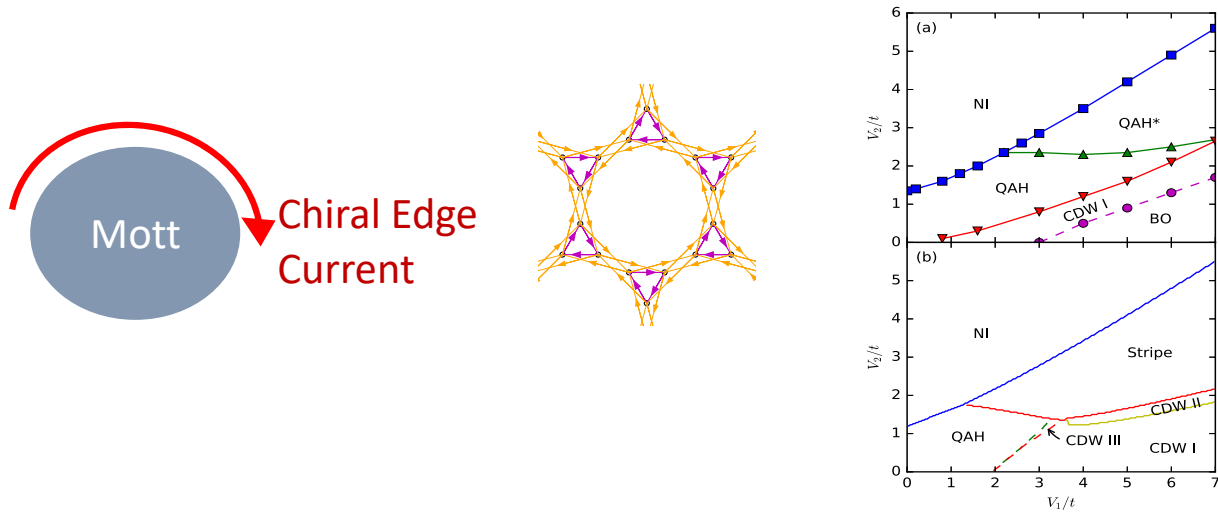
Left: Results from atomic gas microscope experiments in Immanuel Bloch's group. The strong disorder prevents thermalization.

Center: Our theory calculations for the same parameters as Choi et al.

Right: Imbalance as function of time for both theory (lines) and experiments (symbols). The close comparison shows that mean field theory is a good approximation. The assertion that many-body localization was observed therefore requires further experiments probing the difference between mean field and experiment since mean field theory does not have many-body localization.

2.6 Quantum anomalous Hall state from spatially decaying interactions on the decorated honeycomb lattice. Chen, M., Hui, H.-Y., Tewari, S., & Scarola, V. W. *Physical Review B*, 97(3), 035114 (2018).

Topological phases typically encode topology at the level of the single particle band structure. But a remarkable new class of models shows that chiral quantum anomalous Hall effects can be driven exclusively by interactions, while the parent non-interacting band structure is topologically trivial. Unfortunately, these models have so far relied on interactions that do not spatially decay and are therefore unphysical. We study a model of spinless fermions on a decorated honeycomb lattice. Using complementary methods, mean-field theory and exact diagonalization, we find a robust quantum anomalous Hall phase arising from spatially decaying interactions. Our finding paves the way for observing the quantum anomalous Hall effect driven entirely by interactions.



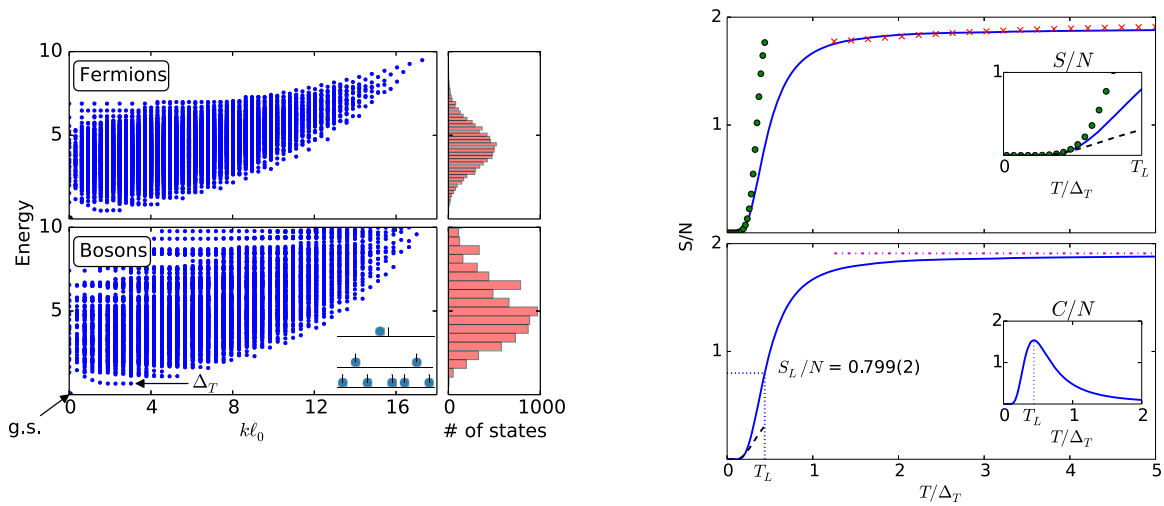
Left: Schematic of chiral currents circulating a topological Mott insulator.

Center: Chiral bond currents in the quantum anomalous Hall phase computed using exact diagonalization

Right: (a) Phase diagram obtained using exact diagonalization on the decorated honeycomb lattice. The symbols are results from calculations and the lines are a guide to the eye. The chiral quantum anomalous Hall phase arises in the center. (b) The same as (a) but the lines plot transitions obtained from self-consistent mean field theory. The agreement between panels (a) and (b) shows strong evidence for a robust chiral state.

2.7 Thermometry for Laughlin States of Ultracold Atoms. Raum, P. T., & Scarola, V. W. Physical Review Letters, 118(11), 115302 (2017).

Cooling atomic gases into strongly correlated quantum phases requires estimates of the entropy to perform thermometry and establish viability. It is currently unknown how cold chiral spin liquids and other topological phases need to be in order to be realized. The chiral spin liquid maps directly onto Laughlin states of bosons. We construct an ansatz partition function for models of Laughlin states of atomic gases by combining high temperature series expansions with exact diagonalization. Using the ansatz we find that entropies required to observe Laughlin correlations, and therefore chiral spin liquids, with bosonic gases are within reach of current cooling capabilities.

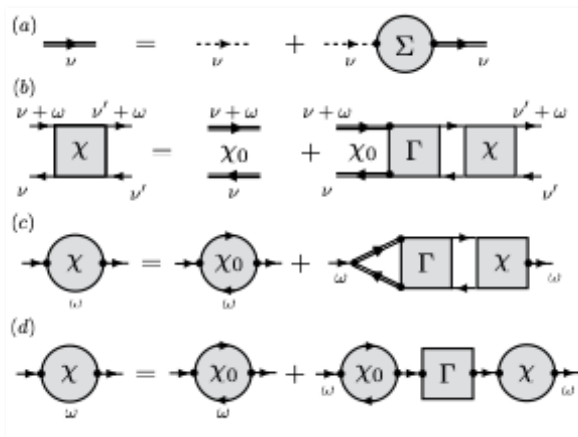


Left: Energy of 8 fermions (bosons) as a function of total wavevector in the lowest Landau level. The ground state is the $k=0$ Laughlin state set to zero energy. The schematic depicts example excitations. The bosonic Laughlin state can be thought of as one filled level of CFs (bosons attached to one flux quantum). Low energy excitations are CF particle-hole pairs. The histograms show nearly Gaussian state counting.

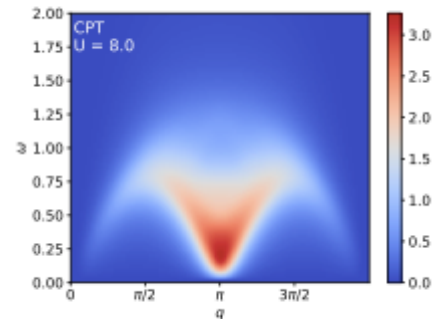
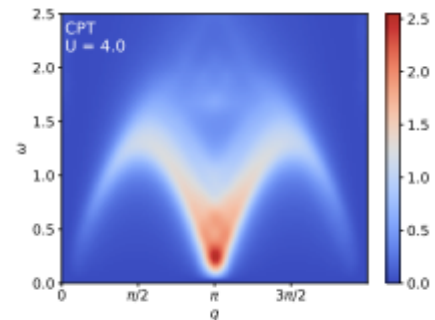
Right: The main panels plot the entropy per particle versus temperature for bosons. The solid lines are obtained from our ansatz. The symbols are other exact results. The agreement between the symbols and the lines shows that the ansatz accurately captures the low and high T limits. The inset plots the heat capacity from the ansatz in the thermodynamic limit. *The number $S/N \sim 0.8$ indicates the first calculation of the entropy needed to realize a Laughlin state with cold atoms.*

2.8 Two-particle correlation functions in cluster perturbation theory: Hubbard spin susceptibilities. Raum, P. T., Alvarez, G., Maier, T., & Scarola, V. W. *Physical Review B*, 101(7), 75122 (2020).

Cluster Perturbation Theory (CPT) is a computationally economic method to estimate the momentum and energy resolved single-particle Green's function. It has been used extensively in direct comparisons with experiments that effectively measure the single-particle Green's function, e.g., angle-resolved photoemission spectroscopy. However, many experimental observables are given by two-particle correlation functions. CPT can be extended to compute two-particle correlation functions by approximately solving the Bethe-Salpeter equation. We implement this method and focus on the transverse spin-susceptibility, measurable via inelastic neutron scattering or with optical probes of atomic gases in optical lattices. We benchmark the method with the one-dimensional Fermi-Hubbard model at half-filling and compare with known results.



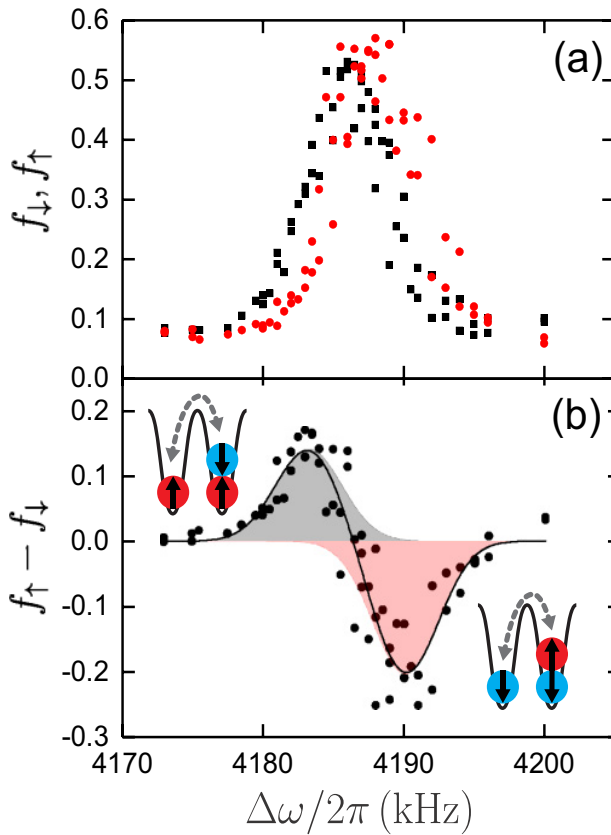
Diagrams used in cluster perturbation theory: (a) the Dyson equation, (b) the Bethe-Salpeter equation for the generalized four-point susceptibility, (c) the Bethe-Salpeter equation for the two-point susceptibility and (d) the analogue of the Dyson equation for the two-point susceptibility. The four-point vertex, $\Gamma(iv, iv', i\omega)$, is approximated by the two-point vertex, $\Gamma(i\omega)$. Dashed lines represent the non-interacting Green's function G_0 , while double lines represent the interacting Green's function G .



CPT approximation to the spin susceptibility for the one-dimensional Hubbard model at half filling plotted as a function of wavevector.

2.9 *Correlated spin-flip tunneling in a Fermi lattice gas.* Xu, W., Morong, W., Hui, H.-Y., Scarola, V. W., & DeMarco, B. *Physical Review A*, 98(2), 023623 (2018).

We report the realization of correlated, density-dependent tunneling for fermionic ^{40}K atoms trapped in an optical lattice. By appropriately tuning the frequency difference between a pair of Raman beams applied to a spin-polarized gas, simultaneous spin transitions and tunneling events are induced that depend on the relative occupations of neighboring lattice sites. Correlated spin-flip tunneling (CSFT) is spectroscopically resolved using gases prepared in opposite spin states, and the inferred Hubbard interaction energy is compared with a tight-binding prediction. We show that the laser-induced correlated tunneling process generates doublons via loss induced by light-assisted collisions. Furthermore, by controllably introducing vacancies to a spin-polarized gas, we demonstrate that correlated tunneling is suppressed when neighboring lattice sites are unoccupied.



Spectroscopy of CSFT. (a) The fraction of atoms transferred between spin states by a 50 m Raman pulse is shown for an initially $|\uparrow\rangle$ (black squares, f_{\uparrow}) and $|\downarrow\rangle$ (red circles, f_{\downarrow}) spin-polarized state at $s = 10 E_R$ for varied $\Delta\omega$. For these measurements, $N = 25400 \pm 3900$ atoms were cooled to $T/T_F = 0.24 \pm 0.08$ before turning on the lattice. Each data point is the result from a single experimental run, and the measurement uncertainty is not visible on this scale. Nonzero transfer at large detuning is due to off-resonant spontaneous Raman scattering. (b) The difference $f_{\uparrow} - f_{\downarrow}$ for pairs of points in (a) reveals the CSFT sidebands at approximately $\pm U$. The black line shows a fit to a sum of two Gaussian functions; the individual Gaussians are displayed as shaded regions. The peak at lower (higher) frequency corresponds to CSFT for an initially $|\uparrow\rangle$ ($|\downarrow\rangle$) spin-polarized state.

3.0 Training Opportunities

Our students and postdoctoral researchers are trained in mathematical and numerical tools used in physics research. We encourage our team members to present at conferences to improve presentation skills and network in the community. We work with group members to improve presentation and writing skills one on one.

Trainee Summary:

- 4 Undergraduates
- 7 Graduate Students
- 3 Postdoctoral Researchers

Supervised Students and Postdocs trained at Virginia Tech:

- Zhangjie Qin (Graduate Student-Current)
- Woo-Ram Lee (Virginia Tech Postdoc-Current)
- Junhua Zhang (Virginia Tech Postdoc-Current)
- Garrett Stoll (Virginia Tech Undergraduate-Current)
- Lance Miller (Virginia Tech Undergraduate-Graduated 2019)
- Peter Raum (Graduate Student-Graduated 2019)
- Hoi Hui (Virginia Tech Postdoc 2015-2018)
- Ben Stern (Undergraduate-Graduated in 2018)
- Mengsu Chen (Graduate Student-Graduated in 2018)
- Mi Yan (Graduate Student-Graduated in 2018)

Supervised Students and Postdocs at Clemson:

- Chuanchang Zeng (Graduate Student-Graduated 2020)
- John Rowe (Undergraduate Student-Graduated 2020)
- Christopher Moore (Graduate Student, Graduated 2020)
- Girish Sharma (Graduate Student, Graduated 2016)

4.0 Results Dissemination

Dissemination Summary:

37 Papers and Preprints
23 Invited Presentations
19 Contributed Presentations

4.1 Papers and Preprints:

1. Raum, P. T., Alvarez, G., Maier, T., & Scarola, V. W. (2020). Two-particle correlation functions in cluster perturbation theory: Hubbard spin susceptibilities. *Physical Review B*, *101*(7), 75122. <https://doi.org/10.1103/PhysRevB.101.075122>
2. Zeng, C., Sharma, G., Stanescu, T. D., & Tewari, S. (2020). Feasibility of measurement-based braiding in the quasi-Majorana regime of semiconductor-superconductor heterostructures. *Physical Review B*, *102*(20), 205101. <https://doi.org/10.1103/PhysRevB.102.205101>
3. Sharma, G., Nandy, S., & Tewari, S. (2020). Sign of longitudinal magnetoconductivity and the planar Hall effect in Weyl semimetals. *Physical Review B*, *102*(20), 205107. <https://doi.org/10.1103/PhysRevB.102.205107>
4. Hofer, S., Datta, T., Tewari, S., & Mazumdar, D. (2020). Topological properties of multilayer magnon insulators. *ArXiv:2008.05487*. <http://arxiv.org/abs/2008.05487>
5. Zeng, C., Nandy, S., & Tewari, S. (2020). Berry curvature dipole in topological Weyl semimetals. *ArXiv:2009.05043*. <http://arxiv.org/abs/2009.05043>
6. Zeng, C., Nandy, S., & Tewari, S. (2020). Fundamental relations for anomalous thermoelectric transport coefficients in the nonlinear regime. *Physical Review Research*, *2*(3), 032066. <https://doi.org/10.1103/PhysRevResearch.2.032066>
7. Sharma, G., Zeng, C., Stanescu, T. D., & Tewari, S. (2020). Hybridization energy oscillations of Majorana and Andreev bound states in semiconductor-superconductor nanowire heterostructures. *Physical Review B*, *101*(24), 245405. <https://doi.org/10.1103/PhysRevB.101.245405>
8. Singh Roy, M., Kumar, M., Sau, J. D., & Tewari, S. (2020). Fermion parity gap and exponential ground state degeneracy of the one-dimensional Fermi gas with intrinsic attractive interaction. *Physical Review B*, *102*(12), 125135. <https://doi.org/10.1103/PhysRevB.102.125135>
9. Sharma, G., Zeng, C., Stanescu, T. D., & Tewari, S. (2020). Hybridization energy oscillations of Majorana and Andreev bound states in semiconductor-superconductor nanowire heterostructures. *Physical Review B*, *101*(24), 245405. <https://doi.org/10.1103/PhysRevB.101.245405>
10. Zeng, C., Sharma, G., Stanescu, T. D., & Tewari, S. (2020). Feasibility of measurement-based braiding in the quasi-Majorana regime of semiconductor-superconductor heterostructures. *Physical Review B*, *102*(20), 205101. <https://doi.org/10.1103/PhysRevB.102.205101>

11. Sharma, G., Nandy, S., & Tewari, S. (2020). Sign of longitudinal magnetoconductivity and the planar Hall effect in Weyl semimetals. *Physical Review B*, *102*(20), 205107. <https://doi.org/10.1103/PhysRevB.102.205107>
12. Hutzler, W., McCord, J. J., Raum, P. T., Stern, B., Wang, H., Scarola, V. W., & Peterson, M. R. (2019). Particle-hole-symmetric model for a paired fractional quantum Hall state in a half-filled Landau level. *Physical Review B*, *99*(4), 045126. <https://doi.org/10.1103/PhysRevB.99.045126>
13. Hui, H.-Y., Chen, M., Tewari, S., & Scarola, V. W. (2019). Flux-driven quantum spin liquids in kagome optical lattices. *Physical Review A*, *100*(5), 053614. <https://doi.org/10.1103/PhysRevA.100.053614>
14. Zeng, C., Stanescu, T. D., Zhang, C., Scarola, V. W., & Tewari, S. (2019). Majorana Corner Modes with Solitons in an Attractive Hubbard-Hofstadter Model of Cold Atom Optical Lattices. *Physical Review Letters*, *123*(6), 060402. <https://doi.org/10.1103/PhysRevLett.123.060402>
15. Zeng, C., Nandy, S., Taraphder, A., & Tewari, S. (2019). Nonlinear Nernst effect in bilayer WT2. *Physical Review B*, *100*(24), 245102. <https://doi.org/10.1103/PhysRevB.100.245102>
16. Sharma, G., & Tewari, S. (2019). Transverse thermopower in Dirac and Weyl semimetals. *Physical Review B*, *100*(19), 195113. <https://doi.org/10.1103/PhysRevB.100.195113>
17. Stanescu, T. D., & Tewari, S. (2019). Robust low-energy Andreev bound states in semiconductor-superconductor structures: Importance of partial separation of component Majorana bound states. *Physical Review B*, *100*(15), 155429. <https://doi.org/10.1103/PhysRevB.100.155429>
18. Nandy, S., Saha, K., Taraphder, A., & Tewari, S. (2019). Mirror anomaly and anomalous Hall effect in type-I Dirac semimetals. *Physical Review B*, *99*(7), 075116. <https://doi.org/10.1103/PhysRevB.99.075116>
19. Zeng, C., Moore, C., Rao, A. M., Stanescu, T. D., & Tewari, S. (2019). Analytical solution of the finite-length Kitaev chain coupled to a quantum dot. *Physical Review B*, *99*(9), 094523. <https://doi.org/10.1103/PhysRevB.99.094523>
20. Nandy, S., Taraphder, A., & Tewari, S. (2019). Planar thermal Hall effect in Weyl semimetals. *Physical Review B*, *100*(11), 115139. <https://doi.org/10.1103/PhysRevB.100.115139>
21. Chen, M., Hui, H.-Y., Tewari, S., & Scarola, V. W. (2018). Quantum anomalous Hall state from spatially decaying interactions on the decorated honeycomb lattice. *Physical Review B*, *97*(3), 035114. <https://doi.org/10.1103/PhysRevB.97.035114>
22. Xu, W., Morong, W., Hui, H.-Y., Scarola, V. W., & DeMarco, B. (2018). Correlated spin-flip tunneling in a Fermi lattice gas. *Physical Review A*, *98*(2), 023623. <https://doi.org/10.1103/PhysRevA.98.023623>
23. Hui, H.-Y., Chen, M., Tewari, S., & Scarola, V. W. (2018). Chiral topological phases in optical lattices without synthetic fields. *Physical Review A*, *98*(2), 023609. <https://doi.org/10.1103/PhysRevA.98.023609>
24. Moore, C., Stanescu, T. D., & Tewari, S. (2018). Two-terminal charge tunneling: Disentangling Majorana zero modes from partially separated Andreev bound states in semiconductor-superconductor heterostructures. *Physical Review B*, *97*(16), 165302. <https://doi.org/10.1103/PhysRevB.97.165302>

25. Sharma, G., Nandy, S., Taraphder, A., & Tewari, S. (2018). Suppression of the Hall number due to charge density wave order in high-Tc cuprates. *Physical Review B*, 97(19), 195153. <https://doi.org/10.1103/PhysRevB.97.195153>
26. Nandy, S., Taraphder, A., & Tewari, S. (2018). Berry phase theory of planar Hall effect in topological insulators. *Scientific Reports*, 8(1), 14983. <https://doi.org/10.1038/s41598-018-33258-5>
27. Dey, U., Chakraborty, M., Taraphder, A., & Tewari, S. (2018). Bulk band inversion and surface Dirac cones in LaSb and LaBi: Prediction of a new topological heterostructure. *Scientific Reports*, 8(1), 14867. <https://doi.org/10.1038/s41598-018-33273-6>
28. Moore, C., Zeng, C., Stanescu, T. D., & Tewari, S. (2018). Quantized zero-bias conductance plateau in semiconductor-superconductor heterostructures without topological Majorana zero modes. *Physical Review B*, 98(15), 155314. <https://doi.org/10.1103/PhysRevB.98.155314>
29. Lin, F., Maier, T. A., & Scarola, V. W. (2017). Disordered Supersolids in the Extended Bose-Hubbard Model. *Scientific Reports*, 7(1), 12752. <https://doi.org/10.1038/s41598-017-13040-9>
30. Raum, P. T., & Scarola, V. W. (2017). Thermometry for Laughlin States of Ultracold Atoms. *Physical Review Letters*, 118(11), 115302. <https://doi.org/10.1103/PhysRevLett.118.115302>
31. Yan, M., Hui, H.-Y., Rigol, M., & Scarola, V. W. (2017). Equilibration Dynamics of Strongly Interacting Bosons in 2D Lattices with Disorder. *Physical Review Letters*, 119(7), 073002. <https://doi.org/10.1103/PhysRevLett.119.073002>
32. Yan, M., Qian, Y., Hui, H.-Y., Gong, M., Zhang, C., & Scarola, V. W. (2017). Spin-orbit-driven transitions between Mott insulators and finite-momentum superfluids of bosons in optical lattices. *Physical Review A*, 96(5), 053619. <https://doi.org/10.1103/PhysRevA.96.053619>
33. Hui, H. Y., Zhang, Y., Zhang, C., & Scarola, V. W. (2017). Superfluidity in the absence of kinetics in spin-orbit-coupled optical lattices. *Physical Review A*, 95(3), 33603. <https://doi.org/10.1103/PhysRevA.95.033603>
34. Chen, M., & Scarola, V. W. (2016). Stability of emergent kinetics in optical lattices with artificial spin-orbit coupling. *Physical Review A*, 94(4), 43601. <https://doi.org/10.1103/PhysRevA.94.043601>
35. Bao, F., Tang, Y., Summers, M., Zhang, G., Webster, C., Scarola, V., & Maier, T. A. (2016). Fast and efficient stochastic optimization for analytic continuation. *Physical Review B*, 94(12), 125149. <https://doi.org/10.1103/PhysRevB.94.125149>
36. Nandy, S., Sharma, G., Taraphder, A., & Tewari, S. (2017). Chiral Anomaly as the Origin of the Planar Hall Effect in Weyl Semimetals. *Physical Review Letters*, 119(17), 176804. <https://doi.org/10.1103/PhysRevLett.119.176804>
37. Sharma, G., Goswami, P., & Tewari, S. (2017). Chiral anomaly and longitudinal magnetotransport in type-II Weyl semimetals. *Physical Review B*, 96(4), 045112. <https://doi.org/10.1103/PhysRevB.96.045112>

4.2 Presentations

Invited Talks by PI Scarola:

Quantum Analogue Simulation with Ultracold Atoms in Optical Lattices: Opportunities and Challenges, Invited Seminar: University of Nevada, Las Vegas February 2020

Colloquium: Quantum Analogue Simulation with Ultracold Atoms in Optical Lattices: Opportunities and Challenges, Virginia Tech, September 2020

Topological Mott Insulators in Certain Frustrated Lattices, Invited Seminar: Ludwig Maximilian University of Munich, Germany November 2019

Quantum Analogue Simulation with Ultracold Atoms in Optical Lattices: Opportunities and Challenges, Invited Seminar: University of Kent Canterbury United Kingdom November 2019

Kavli Institute for physics conference: Emergent phenomena in ultracold atoms: merging topology, interaction, and dynamics, Beijing China “Compressibility Measures of Ultracold Atomic Gases in Optical Lattices“ June 22nd, 2019

Seminar: Duke University “Topological Mott Insulators in Certain Frustrated Lattices” April 11th, 2019

Seminar: Simon Fraser “Compressibility Measures of Ultracold Atomic Gases in Optical Lattices” July 7th, 2019

Seminar: University of Victoria “Compressibility Measures of Ultracold Atomic Gases in Optical Lattices” July 4th, 2019

International conference on Photonics, Optoelectronics and Display Devices, Philadelphia, PA "Optical signatures of excitations in fractional quantum Hall states" Sept. 19, 2018

Atomic Gas Microscopes: Tools for Quantum Emulation and Prospects for Quantum Information Processing” June 12, 2018 Oak Ridge National Laboratory, Oak Ridge TN

“Topological Mott Insulators in Certain Frustrated Lattices” Workshop on Innovative Nanoscale Devices and Systems Nov. 28, 2017 Kona, HI

Invited Talks by PI Tewari:

Seminar: Tata Institute of Fundamental Research, Hyderabad, India, “Partially separated Majorana modes in semiconductor heterostructures”, June 8, 2021

Seminar: Indian Institute of Technology, Delhi, India, “Topological superconductors and Majorana fermions-II”, Mar 5, 2021

Seminar: Indian Institute of Technology, Delhi, India, “Topological superconductors and Majorana fermions-I”, Mar 4, 2021

Seminar: Oak Ridge National Laboratory, Oak Ridge, TN, "The Last Roadblock to Majorana Zero Modes and Topological Quantum Computation in Semiconductor Heterostructures" March 20, 2020

Seminar: University of Augusta, Augusta, Georgia, "The Last Roadblock to Majorana Zero Modes and Topological Quantum Computation in Semiconductor Heterostructures" March 22, 2019

Partially separated Andreev bound states: the last roadblock to Majorana fermions in semiconductor-superconductor heterostructures, Sumanta Tewari, Spintronics XIII San Diego, Aug. 24-28, 2020 (cancelled)

Partially separated Andreev bound states: State of the art of Majorana fermions and topological quantum computation in semiconductor-superconductor heterostructures, Indian Institute of Technology, Delhi, India, July 21, 2020 (online).

Seminar: Indian Institute of Technology, Kharagpur, India “Majorana zero modes: Recent experiments and last roadblock to topological quantum computation in semiconductor heterostructures.” August 13, 2019

“Robust low energy Andreev bound states and quantized tunneling peak in Majorana systems”, July 17, 2017, Workshop on Open Quantum Systems, International Center for Theoretical Science (ICTS), Bangalore, India

“Partially separated Andreev bound states: the last roadblock to Majorana fermions in topological superconductors”, Feb. 26, 2018, Department of Physics, Virginia Polytechnic Institute and State University, VA, USA

“Partially separated Andreev bound states: the last roadblock to Majorana fermions in topological superconductors”, May 18, 2018, Southeast Quantum Computing Workshop, University of Georgia, Athens, GA, USA

“Topological superconductors, Andreev bound states, and Majorana zero modes”, June 28, 2018, S. N. Bose National Centre for Basic Sciences, Kolkata, India.

Contributed Talks by Tewari and Scarola Groups

2021 APS March Meeting (Virtual)

Stabilizing topological superfluidity of cold fermions in two-dimensional optical lattices
Quantification of entanglement in small one-dimensional cluster states
Measurement-based algorithms for quantum simulation of many-body fermionic systems
Quantum Hall-like transitions in the thermal Hall behavior of multilayer topological magnon insulators

2019 APS March Meeting (Boston, MA)

Cluster Perturbation Theory Applied to Two-Particle Correlation Functions
A Particle-Hole-Symmetric Model for Paired Fractional Quantum Hall States in a Half-filled Landau Level
Topological Phases of Fermions in Kagome Optical Lattices
Kitaev chain with a quantum dot
Quantized zero bias conductance plateaus in hybrid nanowire topological quantum information processing platforms without non-Abelian Majorana zero modes

2018 APS March Meeting (Los Angeles, CA)

Topological phases from dipolar interactions on kagome optical lattices
Topological Mott Insulators in Certain Frustrated Lattices
Chiral anomaly as origin of planar Hall effect in Weyl semimetals
Majorana bound states in non-homogeneous semiconductor nanowires

2017 APS March Meeting (New Orleans, LA)

Equilibration Dynamics of Strongly Interacting Bosons in 2D Lattices with Disorder
Stability of Emergent Kinetics in Optical Lattices with Artificial Spin-Orbit Coupling
Superfluidity in the absence of kinetics in spin-orbit- coupled optical lattices
Thermometry for Laughlin States of Ultracold Atoms
Density Assisted Tunneling of Fermions in Optical Lattices
Yu-Shiba-Rusinov states and topological superconductivity in Ising paired superconductors

5.0 Honors and Awards

- “University Research, Scholarship and Artistic Achievement Award, 2018”
Awarded by Clemson University to S. Tewari

6.0 Other Collaborators

1. G. Alvarez, Computer Science and Mathematics Division, Oak Ridge, Tennessee 37831
2. T. Maier, Computer Science and Mathematics Division, Oak Ridge, Tennessee 37831
3. T. Stanescu, Department of Physics and Astronomy, West Virginia University, Morgantown, West Virginia 26506
4. S. Nandy, University of Virginia, Charlottesville, Virginia 22904
5. S. Hofer, Physics Department, 1245 Lincoln Drive, Southern Illinois University, Carbondale, IL 62901
6. T. Datta, Department of Chemistry and Physics, Augusta University, 1120 15th Street, Augusta, Georgia 30912
7. D. Mazumdar, Physics Department, 1245 Lincoln Drive, Southern Illinois University, Carbondale, IL 62901
8. M. Roy, S. N. Bose National Centre for Basic Sciences, Block JD, Sector III, Salt Lake, Kolkata 700106, India
9. M. Kumar, S. N. Bose National Centre for Basic Sciences, Block JD, Sector III, Salt Lake, Kolkata 700106, India
10. J. Sau, Condensed Matter Theory Center and Joint Quantum Institute, Department of Physics, University of Maryland, College Park, Maryland 20742
11. W. Hutzler, Department of Physics & Astronomy, California State University Long Beach, Long Beach, California 90840
12. J. J. McCord, Department of Physics & Astronomy, California State University Long Beach, Long Beach, California 90840
13. H. Wang Shenzhen Institute for Quantum Science and Engineering, and Department of Physics, Southern University of Science and Technology, Shenzhen 518055, China
14. M. R. Peterson Department of Physics & Astronomy, California State University Long Beach, Long Beach, California 90840
15. C. Zhang Department of Physics, The University of Texas at Dallas, Richardson, Texas 75080
16. Taraphder School of Basic Sciences, Indian Institute of Technology Mandi, Kamand 175005, India
17. K. Saha, Max-Planck Institute for the Physics of Complex Systems, D-01187 Dresden, Germany
18. Apparao M., Rao Department of Physics and Astronomy, Clemson University, Clemson, South Carolina 29634
19. W. Xu ,Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801
20. W. Morong, Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801
21. B. DeMarco, Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801
22. U. Dey, Centre for Theoretical Studies, Indian Institute of Technology Kharagpur, Kharagpur, 721302, India
23. M. Chakraborty Centre for Theoretical Studies, Indian Institute of Technology Kharagpur, Kharagpur, 721302, India

24. T. Taraphder, Centre for Theoretical Studies, Indian Institute of Technology Kharagpur, Kharagpur, 721302, India
25. F. Lin, Department of Physics, Virginia Tech Blacksburg, VA 24061
26. M. Rigol, Department of Physics, The Pennsylvania State University, University Park, Pennsylvania 16802
27. Yinyin Qian, Department of Physics, The University of Texas at Dallas, Richardson, Texas 75080
28. Ming Gong, Department of Physics, The University of Texas at Dallas, Richardson, Texas 75080
29. Y. Zhang, Department of Physics, Shanghai University, 200444 Shanghai, China
30. F. Bao, Computer Science and Mathematics Division, Oak Ridge, Tennessee 37831
31. Y. Tang, Department of Physics, Virginia Tech Blacksburg, VA 24061
32. M. Summers, Computer Science and Mathematics Division, Oak Ridge, Tennessee 37831
33. G. Zhang, Computer Science and Mathematics Division, Oak Ridge, Tennessee 37831
34. C. Webster, Computer Science and Mathematics Division, Oak Ridge, Tennessee 37831
35. P. Goswami, Condensed Matter Theory Center and Joint Quantum Institute, Department of Physics, University of Maryland, College Park, Maryland 20742