REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
12-08-2017	Final Report	15-Jun-2011 - 14-May-2017

4. TITLE AND SUBTITLE
Final Report: Exotic Phases of Ultracold Gases

5a. CONTRACT NUMBER
W911NF-11-1-0230

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

6. AUTHORS

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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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)
57957-PH.33

12. DISTRIBUTION AVAILIBILITY 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	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			W. Vincent Liu
UU	UU	UU	UU		19b. TELEPHONE NUMBER 412-624-9023

RPPR Final Report
as of 30-Aug-2017

Agency Code:

Proposal Number: 57957PH **Agreement Number: W911NF-11-1-0230**
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DUNS Number: 004514360 EIN: 250965591
Report Date: 14-Aug-2017 Date Received: 12-Aug-2017
Final Report for Period Beginning 15-Jun-2011 and Ending 14-May-2017
Title: Exotic Phases of Ultracold Gases
Begin Performance Period: 15-Jun-2011 **End Performance Period:** 14-May-2017
Report Term: 0-Other

Submitted By: W. Vincent Liu Email: wvliu@pitt.edu
Phone: (412) 624-9023

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

STEM Degrees: 2 **STEM Participants:** 2

Major Goals: The proposed research involves concepts of basic interest in quantum matter theory (e.g., superfluidity and supersolidity) as well as new ideas on emergent orbital symmetries and exotic quantum phases (e.g., $p_x + ip_y$ chiral topological superfluids and quantum orbital models). It aims to advance our understanding of many-particle physical systems at the cutting-edge research forefronts including beyond-standard cold atomic gases, novel forms of optical lattices, and artificial electronic materials of desired properties. It has the potential of motivating future experiments. The proposed program compliments other exciting programs in the field around the world.

The proposed research focuses on two major topics. One concerns the physics of cold atoms in the high symmetric orbitals of optical lattices. Another studies possible novel effects of momentum-dependent interaction on ensembles of bosons and fermions. Both aim to discover and understand novel emergent symmetries and quantum phases relevant to correlated atomic and molecular quantum matter beyond standard quantum regimes.

The methods employed in the projects are mainly field theoretical techniques. The proposed research also aims to develop new theoretical methods to handle the novel conditions of quantum gases in controlled approximation. They are expected to impact on the future framework for studying novel electronic materials.

Accomplishments: We carried out research in all the proposed topics as well as related frontiers during grant support. The supported research has resulted in 26 published articles, including 2 in Nature Physics, 7 in PRL, 2 in Nature Communications, and 26 invited talks in major conferences by the PI and postdocs. A notable success is the project of optical lattice orbital physics, which has gained considerable attention in recent years. PI's contribution includes having published one of the earliest theoretical papers that started this field. Throughout the support period, the PI's team remains a world leading group of this field, as evidenced by the invited talks and review articles.

The supported research, while being theoretical, have had direct impact on experimental directions. The theoretical research of p-orbital bosons on the optical lattices has led to the new experimental setups by the world's most eminent experimental groups such as I. Bloch and A. Hemmerich. Our prediction of chiral p_x+ip_y Bose-Einstein condensate was tested and confirmed by experiments [A. Hemmerich et al, Nature Physics, 2011; Phys. Rev. Lett. 2015; etc.]. New orbital fermion experiments, directly based on our prediction, are underway by Hulet group at Rice.

For more detailed description of accomplishments, please see the attached "technical report."

RPPR Final Report
as of 30-Aug-2017

Training Opportunities: Nothing to Report

Results Dissemination: Nothing to Report

Honors and Awards: • B. Huang (postdoc), Cornell Summer School poster competition award, 2017.
• XiaopengLi(graduatestudent),selectedasthesoletheoryJQIPostdocFellowinthecompe- tition of over 150 applicants in the year of 2013, Univ of Maryland, College Park. Fellowship from Oct 2013 -2016.
• Xiaopeng Li (graduate student), Graduate Fellowship of KITP (Kavli Institute for Theoreti- cal Physics), UC Santa Barbara, Spring term 2013.
• Xiaopeng Li (graduate student), A. W. Mellon Fellowship of the University of Pittsburgh, 2012-2013
• Xiaopeng Li (graduate student), A. W. Mellon Fellowship of the University of Pittsburgh, 2011-2012

Protocol Activity Status:

Technology Transfer: Nothing to Report

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International Collaboration:
International Travel:
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Project Contribution:
International Collaboration:
International Travel:
National Academy Member:
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Project Contribution:
International Collaboration:
International Travel:
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Project Contribution:
International Collaboration:
International Travel:
National Academy Member:
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RPPR Final Report
as of 30-Aug-2017

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Project Contribution:
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Project Contribution:
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Project Contribution:
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International Travel:
National Academy Member:
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Project Contribution:
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Project Contribution:
International Collaboration:
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Project Contribution:
International Collaboration:
International Travel:
National Academy Member:
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International Travel:
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Project Contribution:
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International Travel:
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International Collaboration:
International Travel:
National Academy Member:
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Project Contribution:
International Collaboration:
International Travel:
National Academy Member:
Other Collaborators:

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Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
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Project Contribution:
International Collaboration:
International Travel:

National Academy Member: N
Other Collaborators:

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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
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Project Contribution:
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International Travel:
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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
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Project Contribution:
International Collaboration:

RPPR Final Report
as of 30-Aug-2017

International Travel:
National Academy Member: N
Other Collaborators:

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevA.83.063626
Volume: 83 Issue: 6 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Effective action approach to the p-band Mott insulator and superfluid transition
Authors:
Keywords: p-band, optical lattice, Mott insulator, superfluid, effective field theory
Abstract: Motivated by the recent experiment on p-orbital-band bosons in optical lattices, we study theoretically the quantum phases of Mott insulator and superfluidity in two dimensions. The system features a superfluid phase with transversely staggered orbital current at weak interaction and a Mott insulator phase with antiferro-orbital order at strong coupling and commensurate filling. We go beyond mean-field theory and derive from a microscopic model an effective action that is capable of describing both the p-band Mott insulating and superfluid phases in strong coupling. We further calculate the excitation spectra near the quantum critical point and find two gapless modes away from the tip of the Mott lobe but four gapless modes at the tip. Our effective theory reveals how the phase coherence peak builds up in the Mott regime when approaching the critical point. We also discuss the finite-temperature phase transition of p-band superfluidity.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.108.175302
Volume: 108 Issue: 17 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Time-Reversal Symmetry Breaking of p-Orbital Bosons in a One-Dimensional Optical Lattice
Authors:
Keywords: p-orbital, time reversal symmetry breaking, ferro-orbital order
Abstract: We study bosons loaded in a one-dimensional optical lattice of two-fold p-orbital degeneracy at each site. Our numerical simulations find an anti-ferro-orbital p$_x$+ip$_y$, a homogeneous p$_x$ Mott insulator phase and two kinds of superfluid phases distinguished by the orbital order (anti-ferro-orbital and para-orbital). The anti-ferro-orbital order breaks time reversal symmetry. Experimentally observable evidence is predicted for the phase transition between the two different superfluid phases. We also discover that the quantum noise measurement is able to provide a concrete evidence of time reversal symmetry breaking in the first Mott phase.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

RPPR Final Report
as of 30-Aug-2017

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevA.84.051603
Volume: 84 Issue: 5 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Orbital order of spinless fermions near an optical Feshbach resonance
Authors:
Keywords: color Hubbard model, optical Feshbach resonance, p-orbital
Abstract: We study the quantum phases of a three-color Hubbard model that arises in the dynamics of the p-band orbitals of spinless fermions in an optical lattice. Strong, color-dependent interactions are induced by an optical Feshbach resonance. Starting from the microscopic scattering properties of ultracold atoms, we derive the orbital exchange constants at 1/3 filling on the cubic optical lattice. Using this, we compute the phase diagram in a Gutzwiller ansatz. We find novel phases with 'axial orbital order' in which pz and px + ipy (or px - ipy) orbitals alternate.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevA.85.053606
Volume: 85 Issue: 5 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Stripe, checkerboard, and liquid-crystal ordering from anisotropic p-orbital Fermi surfaces in optical lattices
Authors:
Keywords: p-orbital fermion, stripe, orbital liquid crystal
Abstract: We study instabilities of single-species fermionic atoms in the p-orbital bands in two-dimensional optical lattices at noninteger filling against interactions. Charge density wave and orbital density wave orders with stripe or checkerboard patterns are found for attractive and repulsive interactions, respectively. The superfluid phase, usually expected of attractively interacting fermions, is strongly suppressed. We also use field theory to analyze the possible phase-transitions from orbital stripe order to liquid-crystal phases and obtain the phase diagram. The condition of nearly-perfect Fermisurface nesting, which is key to the above results, is shown robustly independent of fermion fillings in such p-orbital systems, and the $(2k_F,\pm2k_F)$ momentum of density wave oscillation is highly tunable. Such remarkable features show the promise of making those exotic orbital phases, which are of broad interest in condensed-matter physics, experimentally realizable with optical lattice gas
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

RPPR Final Report
as of 30-Aug-2017

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Nature Physics
Publication Identifier Type: DOI Publication Identifier: 10.1038/nphys2134
Volume: 8 Issue: 1 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Topological semimetal in a fermionic optical lattice
Authors:
Keywords: topological semimetal, orbital band, double-well optical lattices, Berry phase
Abstract: Optical lattices have an important role in advancing our understandingof correlated quantum matter. The recent implementation of orbital degrees of freedom in chequerboard and hexagonal optical lattices opens up a new avenue towards discovering novel quantum states of matter that have no prior analogues in solid-state electronic materials. Here, we predict that an exotic topological semimetal emerges as a parity-protected gapless state in the orbital bands of a two-dimensional fermionic optical lattice. This new quantum state is characterized by a parabolic band-degeneracy point with Berry flux 2?, in sharp contrast to the ? flux of Dirac points as in graphene. We show that the appearance of this topological liquid is universal for all lattices with D4 point-group symmetry, as long as orbitals with opposite parities hybridize strongly with each other and the band degeneracy is protected by odd parity. Turning on inter-particle repulsive interactions, the system undergoes a phase transi
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevA.95.063619
Volume: 95 Issue: 6 First Page #:
Date Submitted: 8/12/17 12:00AM Date Published: 6/1/17 4:00AM
Publication Location:
Article Title: Effective theory of interacting fermions in shaken square optical lattices
Authors: Ahmet Kele?, Erhai Zhao, W. Vincent Liu
Keywords: shaken optical lattice, superfluid
Abstract: We develop a theory of weakly interacting fermionic atoms in shaken optical lattices based on the orbital mixing in the presence of time-periodic modulations. Specifically, we focus on fermionic atoms in circularly shaken square lattice with near resonance frequencies, i.e., tuned close to the energy separation between s-band and the p-bands. First, we derive a time-independent four-band effective Hamiltonian in the non-interacting limit. Diagonalization of the effective Hamiltonian yields a quasi-energy spectrum consistent with the full numerical Floquet solution that includes all higher bands. In particular, we find that the hybridized s-band develops multiple minima and therefore non-trivial Fermi surfaces at different fillings. We then obtain the effective interactions for atoms in the hybridized s-band analytically and show that they acquire momentum dependence on the Fermi surface even though the bare interaction is contact-like. We apply the theory to find the phase diagram of f
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 30-Aug-2017

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.119.050401
Volume: 119 Issue: 5 First Page #:
Date Submitted: 8/12/17 12:00AM Date Published: 7/1/17 8:00AM
Publication Location:
Article Title: Frustrated Magnetism of Dipolar Molecules on a Square Optical Lattice: Prediction of a Quantum Paramagnetic Ground State
Authors: Haiyuan Zou, Erhai Zhao, W. Vincent Liu
Keywords: Spin liquid, cold atom, dipolar, Heisenburg
Abstract: Motivated by the experimental realization of quantum spin models of polar molecule KRb in optical lattices, we analyze the spin 1/2 dipolar Heisenberg model with competing anisotropic, long-range exchange interactions. We show that, by tilting the orientation of dipoles using an external electric field, the dipolar spin system on square lattice comes close to a maximally frustrated region similar, but not identical, to that of the J1-J2 model. This provides a simple yet powerful route to potentially realize a quantum spin liquid without the need for a triangular or kagome lattice. The ground state phase diagrams obtained from Schwinger-boson and spin-wave theories consistently show a spin disordered region between the Né el, stripe, and spiral phase. The existence of a finite quantum paramagnetic region is further confirmed by an unbiased variational ansatz based on tensor network states and a tensor renormalization group.
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: Reports on Progress in Physics
Publication Identifier Type: DOI Publication Identifier: 10.1088/0034-4885/79/11/116401
Volume: 79 Issue: 11 First Page #: 116401
Date Submitted: 8/12/17 12:00AM Date Published: 11/1/16 4:00AM
Publication Location:
Article Title: Physics of higher orbital bands in optical lattices: a review
Authors: Xiaopeng Li, W Vincent Liu
Keywords: review, orbital optical lattice
Abstract: Orbital degree of freedom plays a fundamental role in understanding the unconventional properties in solid state materials. Experimental progress in quantum atomic gases has demonstrated that high orbitals in optical lattices can be used to construct quantum emulators of exotic models beyond natural crystals, where novel many-body states such as complex Bose-Einstein condensation and topological semimetals emerge. A brief introduction of orbital degree of freedom in optical lattices is given and a summary of exotic orbital models and resulting many-body phases is provided. Experimental consequences of the novel phases are also discussed.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 30-Aug-2017

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevA.94.031602
Volume: 94 Issue: 3 First Page #:
Date Submitted: 8/12/17 12:00AM Date Published: 9/1/16 4:00AM
Publication Location:
Article Title: Detecting ? -phase superfluids with p-wave symmetry in a quasi-one-dimensional optical lattice
Authors: Bo Liu, Xiaopeng Li, Randall G. Hulet, W. Vincent Liu
Keywords: orbital, optical lattice, pairing, one dimension
Abstract: We propose an experimental protocol to study p-wave superfluidity in a spin-polarized cold Fermi gas tuned by an s-wave Feshbach resonance. A crucial ingredient is to add a quasi-1D optical lattice and tune the fillings of two spins to the s and p band, respectively. The pairing order parameter is confirmed to inherit p-wave symmetry in its center-of-mass motion. We find that it can further develop into a state of unexpected ?-phase modulation in a broad parameter regime. Measurable quantities are calculated, including time-of-flight distributions, radio-frequency spectra, and in situ phase-contrast imaging in an external trap. The ?-phase p-wave superfluid is reminiscent of the ?-state in superconductor-ferromagnet heterostructures but differs in symmetry and origin. If observed, it would represent another example of p-wave pairing, first discovered in He-3 liquids.

Acknowledged Federal Support: **Y**

Final Report

Exotic phases of ultracold gases

Proposal Number: 57957-PH
Grant Number: W911NF-11-1-0230
Period: Jun 15, 2011- May 14, 2017

Prepared by
W. Vincent Liu
Organization: University of Pittsburgh
August 12, 2017

Abstract

We carried out research in all the proposed topics as well as related frontiers during grant support. The supported research has resulted in 26 published articles, including 2 in *Nature Physics*, 7 in *PRL*, 2 in *Nature Communications*, and 26 invited talks in major conferences by the PI and postdocs. A notable success is the project of optical lattice orbital physics, which has gained considerable attention in recent years. PI's contribution includes having published one of the earliest theoretical papers that started this field. Throughout the support period, the PI's team remains a world leading group of this field, as evidenced by the invited talks and review articles.

The supported research, while being theoretical, have had direct impact on experimental directions. The theoretical research of p-orbital bosons on the optical lattices has led to the new experimental setups by the world's most eminent experimental groups such as I. Bloch and A. Hemmerich. Our prediction of chiral $p_x + ip_y$ Bose-Einstein condensate was tested and confirmed by experiments [A. Hemmerich *et al*, Nature Physics, 2011; Phys. Rev. Lett. 2015; etc.]. New orbital fermion experiments, directly based on our prediction, are underway by Hulet group at Rice.

1 Introduction

This is the final report for the proposal titled "Exotic phases of ultracold gases." It is organized as follows. Section 2 outlines the major goals. Section 3 describes the technical aspects of the scientific progress and accomplishment. Section 4 reports the impact of the supported research viewed from scholarly activities. Section 5 reports collaborative research activities. Section 6 lists papers published in the reporting period.

2 Major Goals

The proposed research involves concepts of basic interest in quantum matter theory (e.g., superfluidity and supersolidity) as well as new ideas on emergent orbital symmetries and exotic quantum

phases (e.g., $p_x + ip_y$ chiral topological superfluids and quantum orbital models). It aims to advance our understanding of many-particle physical systems at the cutting-edge research forefronts including beyond-standard cold atomic gases, novel forms of optical lattices, and artificial electronic materials of desired properties. It has the potential of motivating future experiments. The proposed program compliments other exciting programs in the field around the world.

The proposed research focuses on two major topics. One concerns the physics of cold atoms in the high symmetric orbitals of optical lattices. Another studies possible novel effects of momentum-dependent interaction on ensembles of bosons and fermions. Both aim to discover and understand novel emergent symmetries and quantum phases relevant to correlated atomic and molecular quantum matter beyond standard quantum regimes.

The methods employed in the projects are mainly field theoretical techniques. The proposed research also aims to develop new theoretical methods to handle the novel conditions of quantum gases in controlled approximation. They are expected to impact on the future framework for studying novel electronic materials.

3 Accomplished Research Projects

In this period, we carried out research with the following projects, summarized below.

(1) *Invited review articles*

- **Review for orbital optical lattices.** (Our work *Rep. Prog. Phys. 2016* [1])
- **News & Views.** "Orbital Dance," a "News & Views" article, *Nature Physics 2011* [2]

(2) *Clean Floquet Time crystal phases: Models and Realizations in Cold Atoms.*

Recent experiments found such Floquet time crystal phase both in the presence and absence of localization, while in all recent theories localization by disorder is usually assumed a priori. In this work, we point out that time crystals can generally exist in systems without disorder. We propose two cold atom experimental schemes to realize the clean Floquet time crystals, one by making use of dipolar gases and another by synthetic dimensions. (Our work *arXiv preprint 2017* [3])

(3) *Novel phases of p-orbital bands of optical lattices - bosons*

(a) **Prediction of the bosonic equivalent of Dirac fermions and topological superconductivity for a cold atom experimental system.** The chiral $p_x \pm ip_y$ Bose-Einstein condensate, as realized in orbital optical lattice experiments at Hamburg, may be viewed as a bosonic variant of the famous 2-dimensional $p_x + ip_y$ superconductivity for electronic materials. Such a Bose cold gas is found to show Dirac bosons with π Berry flux in excitation spectrum. Quite remarkably, when adding a potential bias to the lattices, this Bose system becomes a topological superfluid: a gap opens up in the excitation spectrum, and the system shows nonzero Chern invariant and topologically protected edge excitation modes. This project is a collaboration with Hamburg experimentalist. The Hamburg

group is now planning the experiments to detect our prediction. (Our work . *Phys. Rev. Lett. 2016* [4])

(b) **Phase diagram of chiral superfluidity, chiral Bose liquid, and two classes of p-band Mott insulators**. Developed effective field theory description (Our work *Phys. Rev. A 2011* [5]).

(c) **Chiral phases of higher orbital band bosons and detection by quench dynamics.** [Our work *Nat. Comm.* [6]; it continues our previous years' work with: *Xu, et al, Phys Rev A87, 013635 (2013);* with Li and Zhao, PRA **83**, 063626 (2011) [5].]

(d) **Landau and dynamical instabilities of the p-orbital band Bose gas in optical lattices** (Our work PRA 2013 [7])

(e) **One-dimensional model of orbital degeneracy.** Proposed a scheme of studying Mott insulator-superfluid transition in a model of two physical conditions previously thought incompatible, namely, orbital degeneracy and *one-dimensional* space (our work *PRL 2012* [8]).

(4) *Novel phases of p-orbital bands of optical lattices - fermions*

(a) **Effective theory of interacting fermions in shaken square optical lattices.** (Our work *Phys. Rev. A 2017* [9])

(b) **Prediction of π-phase p-wave superfluids and experimental detecting protocol.** (Our collaborative work with AMO experimentalist R. Hulet at Rice *Phys. Rev. A 2016* [10])

(c) **Spin-orbital exchange of strongly interacting fermions**. An idea to use optical lattices to study the models of spin and orbital degeneracy pertinent to transition metal oxides. (Our work *Phys. Rev. Lett. (2015a)* [11])

(d) **Orbital liquid crystal phases of cold fermions in optical lattices.** (Our work *PRA 2012* [12])

(e) **Three-color Hubbard model** (our work PRA 2011 [13]).

(5) *Topological phases*

(a) **Spontaneous quantum Hall effect in a spinor Bose-Fermi mixture, without artificial gauge field.** (Our work *Phys. Rev. Lett. (2015b)* [14])

(b) **Novel topological superfluidity by breaking centrosymmery in an optical lattice.** (Our work *Phys. Rev. A, Rapid Communication* [15]) Here we report that, without engineering gauge flux or synthetic spin-orbital coupling by some advanced or complex techniques, topological non-trivial Bloch bands can arise naturally in an optical lattice of novel symmetry, i.e., noncentrosymmetric. We find such a topological superfluid supports Majorana fermions.

(c) **Optical Raman lattice and chiral topological orders.** (Our work [16]) We find an optical Raman lattice without spin-orbit coupling showing chiral topological orders for cold atoms.

(d) **First theoretical prediction of topological (center-of-mass) $p_x + ip_y$-wave superfluidity from an s-wave interaction.** This state is topological. A key ingredient is to pair fermions from the *parity odd and even* bands. (Our work *Nature Commun. (2014)* [17]).

Highlights:

i. Recognized by expert as an "important topic." **Wolfgang Ketterle** gave a 20-min lecture in "Grand Challenges in Quantum Fluids and Solids" Workshop at Buffalo, August 7 - 9, 2015. (Conference website: http://sites.psu.edu/qfs2015/.) He included our work as one of the top topics in his list.

ii. This is a key project in the original proposal, so we will provide some details below for this project.
Technical detail— In this work, we introduced a multiple-orbital optical lattice model and discovered that a new class of p-wave superfluid states occurs from a purely s-wave interaction, requiring neither spin-orbit coupling nor an induced p-wave interaction. Such a p-wave state exhibits the highly sought-after topological properties such as topologically protected zero modes. The new pairing mechanism we find here makes the superfluid transition temperature by orders of magnitude higher than the conventional relative-motion $p_x + ip_y$ state. We expect this work to have significant impacts on the topics of superconductivity and topological phases in both electronic and atomic quantum materials.

(e) **Topological optical lattice ladder** (*Nat. Comm.* [18] and *PRA* [19]).

(f) **Topological semimetal in optical lattices** (Our work *Nature Physics (2012)* [20])

(6) *Strongly correlated quantum models.*

(a) **Prediction of a Quantum Paramagnetic Ground State of a dipolar spin 1/2 Heisenberg model in a simple and easy-to-realize square lattice**. This provides a simple yet powerful route to potentially realize a quantum spin liquid without the need for a triangular or kagome lattice. (Our work *Phys. Rev. Lett. 2017* [21])

(b) **Proposed a "tripod" model that shows transition of three fundamentally important compass-type models—Ising model, the Kitaev model, and the quantum** 120° **model— and beyond by tuning a single parameter** (Our work *New J. Phys.* [22]) This project points to a different, "orbital-based" direction than the main stream, in the goal of searching for the sought-after "spin liquid" phases that has the quasi-particles of fractional statistics, namely, *anyons*. Here the idea is to map the degenerate orbital degrees of freedom to the physics of pseudo-spins.

(7) *Prediction of Weyl superfluidity for dipolar Fermi gases when applying a rotating field.* (Our work *Phys. Rev. Lett. (2015c)* [23])

(8) *Bose-Einstein supersolid.* Found Bose-Einstein supersolid phase for a novel class of momentum dependent (non-local) interaction between bosons. This finding is consistent with a recent

independent exact numerical study by Cinti, Zoller et al [arXiv:1005.2403]. (Our work *PRA 2011* [24])

(9) *Impact beyond cold atoms:*

(a) **magnetic order in electronic oxide materials with degenerate** (d_{xy}, d_{yz}, d_{xz}) **orbitals** (*Phys. Rev. Lett. 2014* [25], selected as "Research Highlight" by *Nature Nanotechnology* vol. 9, 245 (2014)).

(b) **KT transition of Larkin-Ovchinnikov phase** (our work *PRB 2011* [26]).

4 Research Impact

4.1 Prediction vs. Experimental Observation

Highlights in relation to cold atom experiments. (i) Hamburg experimental group reported "Observing Chiral Superfluid Order by Matter-Wave Interference" (PRL March 2015). Their experiment is the latest experimental evidence for the $p_x \pm ip_y$ novel Bose superfluid we predicted.

(ii) Hamburg group has set up new plans to test another outstanding prediction by our research, namely, the concepts of Dirac bosons, π-flux, and bosonic edge states in the chiral BEC (our joint work with Hemmerich [4]; also by A. Hemmerich, private communication, 2017).

(iii) We recently completed a joint paper with Randy Hulet at Rice University [10]. The proposed experiment for p-band fermions is being planned by the Hulet group with a gas of ^{6}Li atoms. The atoms are expected to be loaded into a 3D optical lattice, with the optical potential made relatively weaker along one of the directions, say z.

4.2 News and Editorial

- Our (*PRL* [25] [with Xiaopeng Li (student), and Leon Balents (UC Santa Barbara)], published in Feb 2014, was selected as **"Research Highlight"** by the Editor of **Nature Nanotechnology** vol. 9, 245 (April issue, 2014) [doi:10.1038/nnano.2014.83]).

4.3 Press Reports

- On Graduate Student Achievement: "Student Xiaopeng Li Named Kavli Institute for Theoretical Physics Graduate Fellow", News of Note From Pitt, University of Pittsburgh, http://www.news.pitt.edu/8_15_NON_13

- On Stuent Achievement - Departmental News: "Xiaopeng Li selected as a 2013 KITP Graduate Fellow in Santa Barbara", Department of Physics and Astronomy, U of Pittsburgh
http://www.physicsandastronomy.pitt.edu/content/xiaopeng-li-selected-2013-kitp-graduate-fellow-santa-barbara

- On Kaufman Fund Award: the PI (Liu) and his colleague (Sergey Frolov, an outstanding young experimentalist on Majorana fermions) selected by Kaufman Foundation of The Pittsburgh Foundation, for the inauguration of the series of New Initiative Research Grant. We are among the three winning teams from three different areas (physics, chemistry and biology), the only one representing Physics. News announced on July 25, 2013. See the News links:
  (i) Pittsburgh Post-Gazette: "Kaufman Foundation awards initial science grants", July 25, 2013 2:00 pm report by Don Hopey
  http://www.post-gazette.com/stories/local/region/kaufman-foundation-awards-initial-science-grants-696885/
  (ii) U of Pittsburgh School of Arts & Science: "PHYSICS PROFESSORS WIN CHARLES E. KAUFMAN FOUNDATION GRANT" ,
  http://www.as.pitt.edu/node/751
  (iii) News of Note From Pitt News: "Physics Professors Sergey M. Frolov and W. Vincent Liu Win Charles E. Kaufman Foundation Grant",
  http://www.news.pitt.edu/7_25NON_13
  (iv) Carnegi-Mellon University Press Release:
  http://www.cmu.edu/mcs/news/pressreleases/2013/0725-kaufman.html

- On topological semimetal in fermionic optical lattices: "Pitt Discoveries in Quantum Physics Could Change Face of Technology", subtitled "Through simple system studies, researchers are unearthing a new quantum state of matter," Office of Public Affairs, Univ of Pittsburgh, Nov 21, 2011. http://www.news.pitt.edu/Nature_QuantumPhysics

- "Topological matter in optical lattices," JQI of University of Maryland and NIST, Press Release, November 23, 2011.
  http://www.jqi.umd.edu/news/289-topological-matter-in-optical-lattices.html

- "Unearthing a new quantum state of matter: Quantum physics discoveries could change face of technology." "Researchers have made advances in better understanding correlated quantum matter that could change technology as we know it, according to a new study." Mon 21 Nov 11 from ScienceDaily,
  http://www.sciencedaily.com/releases/2011/11/111121142459.htm

- More news reports on the discovery of "topological matter in optical lattices" by the PI and his collaborators may be found at: Physics News,
  http://www.physnews.com/physics-news/cluster196774764/

4.4 Major research articles

- Two Nature Physics articles: *Nature Physics (2012)* [20]; *Nature Physics 2011* [2]

- One long review: *Rep. Prog. Phys. 2016* [1]

4.5 Invitations to Colloquiums, Conferences and Research Programs (skip seminars)

PI'S INVITATIONS - SELECTED LIST

3-7 Jul 2017	Invited talk, Workshop on "Quantum Connections in Sweden", Stockholm University, Albanova University Center, Sweden
18-22 Jun 2016	Invited talk, International Symposium on Cold Atom Physics - ISCAP VII, Hangzhou, China
10 Oct 2016	Kavli Inst for Theoretical Physics, UCSB. KITP "Synthetic Quantum Matter" Program Talk: "informal discussion: center-of-mass p+ip-wave fermion pairing."
09/26–10/14/2016	invited participant, KITP Program "Synthetic Quantum Matter," Kavli Institute for Theoretical Physics, University of California, Santa Barbara
11/02-20/2015	Invited participant, KITP Program "Many-Body Physics with Light," Kavli Institute for Theoretical Physics, University of California, Santa Barbara
9/14-10/02/2015	Invited participant, KITP Program "New Phases and Emergent Phenomena in Correlated Materials with Strong Spin-Orbit Coupling", Kavli Institute for Theoretical Physics, University of California, Santa Barbara
31 Aug-4 Sep 2015	Invited talk, International workshop on "Synthetic Quantum Magnetism", Max Planck Institute for the Physics of Complex Systems (MPIPKS), Dresden, Germany
28 Apr 2015	Seattle INT Program talk: "Chiral Bose and Fermi phases in optical lattices, Program "Frontiers in Quantum Simulation with Cold Atoms", Institute for Nuclear Theory, University of Washington, Seattle
14 Nov 2014	Colloquium, Department of Physics, College of William & Mary, Williamsburg, VA
6 Nov 2014	Colloquium, Department of Physics, SUNY Buffalo
2 Sep 2014	Invited Short Blackboard Talk, in "Gauge Fields in Condensed Matter, Ultracold atoms and beyond" Program, Aspen Center for Physics
14-17 Jun 2014	6th International Symposium on Cold Atom Physics - ISCAP VI, Taiyuan, China. Invited talk: "Orbital phases in beyond-standard optical lattices".
24-25 Sep 2013	Army Science Planning & Strategy Meeting: Quantum Information and Sensing, Bolger Conference Center in Potomac, Maryland (Washington DC sub), invited talk: "Topological orbital physics of cold atoms in novel lattice geometries — a possible future direction for the Army"

10-24 Aug 2013	Aspen Summer Program “Optical Lattice Emulators and Beyond”, Aug 4-25, 2013, Aspen Center for Physics, Aspen. Invited participant (2 weeks, Aug 11-25, 2013)
8-10 Jul 2013	“Cold Atoms" Summer School of Department of Physics, Tsinghua University, Beijing. Pedagogical lecture: “Selected Topics in Modern Many-Body Theory"
28-30 Jun 2013	7th Cross-Strait and International Conference on Quantum Manipulation, Institute of Physics, Chinese Academy of Sciences (CAS), Beijing. Invited speaker: “Topological phases of fermions in the p-orbital band of optical lattices”
19-21 Jun 2013	International Workshop on “Quantum Many-Body Systems in Low Dimensions”, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan, China. Invited long talk: “Orbital phase transitions in low dimensional beyond-standard optical lattices”
25-26 Feb 2013	Symposium on ‘Novel Topological Quantum Matter’, University of Texas at Dallas campus: Discussion Leader for Session “Future Directions”
4 Feb 2013	Nordita Workshop “Pushing the Boundaries with Cold Atoms", NORDITA, KTH and Stockholm University, Stockholm, Sweden, Feb 1-10, 2013. Invited Speaker/Participant: “Topological phases of fermions in the p-orbital band of optical lattices”
6 Dec 2012	Tsinghua University, Department of Physics Colloquium: “Orbital dance beyond standard optical lattices", Beijing, China
24 Oct 2012	U Texas at Dallas Physics Colloquium: “Orbital dance beyond standard optical lattices,” Dallas, TX
17 Oct 2012	KITP Santa Barbara “Quantum Dynamics” Program Talk: “Topological orbital phases beyond standard optical lattices,” UC Santa Barbara
26 Apr 2012	Kent State University, Department of Physics Colloquium: “Ultracold atoms tuned to many-body regimes previously impossible”, Kent, OH
23-27 June 2012	The 5th International Symposium on Cold Atom Physics (ISCAP-V), Three Gorges, China. Invited talk: “Topological orbital gases in optical lattices”
14 Oct 2011	University of New Brunswick, Department of Physics, Colloquium: “Ultracold atoms tuned to new many-body regimes”, Fredericton, Canada
18-22 July 2011	Advanced Workshop on “Non-standard superfluids and insulators”, ICTP, Trieste, Italy, invited talk: “p-band superfluid and insulator phases in optical lattices”

13 July 2011 Universitaet Hamburg, Institute of Laser Physics, Colloquium of the Center for Optical Quantum Technologies: "Ultracold atoms in the unprecedented regimes of condensed matter"

4.6 Talks and Conference Activities by group members

INVITED TALKS BY STUDENTS/POSTDOCS

1. Zhifang XU (postdoc), Invited talk: Emergent gauge fields in an atomic spinor Bose-Fermi mixture, "New Developments in Cold Atom Physics and Related Topics", Institute for Advanced Study, Tsinghua University, Beijing, China, January 4, 2015.

2. Xiaopeng Li (grad student), APS Invited talk: "Orbital physics in one dimensional optical lattice", APS March Meeting in Baltimore (18 March 2013)

3. Xiaopeng Li, invited seminar: "1D quantum orbital gases on optical lattices", JILA NIST-U of Colorado public seminar in Boulder, Colorado (13 Dec 2012)

CONTRIBUTED TALKS AND CONFERENCE ACTIVITIES BY STUDENTS/POSTDOCS

4. B. Huang, "Quantum Spin Liquids in Hyperhoneycomb Lattices: Classifications and Applications to Pressurized β-Li_2IrO_3", contributed talk, APS March Meeting 2017, New Orleans, LA, March 13-17, 2017.

5. B. Huang, "Clean Floquet time crystals: Models and realizations in cold atoms", poster, Pittsburgh Quantum Institute Event, April 26-28, 2017.

6. B. Huang, "Mott Time Crystal: Models and Realizations in Cold Atoms", contributed talk, Sacramento, CA, June 5-9, 2017.

7. B. Huang, "Clean Floquet time crystals: Models and realizations in cold atoms", poster, Cornell Summer School on Emergent Phenomena in Quantum Materials, May 31-June 02, 2017.

8. Ahmet Keles, "Fermions on the Bloch bands of shaken square optical lattice", APS March Meeting 2017, New Orleans, LA, March 13-17, 2017.

9. Ahmet Keles, Quantum Revolutions, Pittsburgh Quantum Institute, Pittsburgh, PA, April 26-28, 2017.

10. Ahmet Keles, Quantum Connections, Stockholm University, Stockholm, Sweden, July 2-8, 2017.

11. B. Liu, Talk: "Detecting π-phase superfluids with p-wave symmetry in a quasi-1D optical lattice", 47th APS DAMOP Meeting in Providence, Rhode Island, May 23 – 27, 2016.

12. Haiyuan Zou, Talk: "A continuum of compass spin models on the honeycomb lattice", 47th DAMOP Meeting in Providence, Rhode Island, May 23 – 27, 2016.

13. M. Arzamasovs, Talk: "Mixed frequency superconductivity in the bode-fermi mixture", Symposium "Quantum Connections 2016", June 2016, NORDITA and Stockholm University, Stockholm, Sweden

14. B. Liu, "Chiral sp-orbital paired superfluid of fermionic atoms in a 2D spin-dependent optical lattice", APS March Meeting in Denver, Colorado, March 2014

15. X. Li, "Orbital coupled dipolar fermions in an asymmetric optical ladder", APS March Meeting in Baltimore, Maryland

16. B. Wang, "Quantum Dynamics of Population-Imbalanced Fermi Mixture in One-dimensional Optical Lattices", APS March Meeting, Boston (2012).

17. X. Li, "Time reversal symmetry breaking of p-orbital bosons in a one-dimensional optical lattice", in Session on "Many-body Quantum Phases in Cold Atom Systems", APS March Meeting, Boston, Massachusetts, Feb 27-March 2, 2012.

18. X. Li, "Topological phase transition in an sp-orbital chain", in Session on "Synthetic Gauge Fields and Optical Lattices", DAMOP Meeting, Orange County, California, June4-8, 2012.

4.7 Recognition

- B. Huang (postdoc), Cornell Summer School poster competition award, 2017.
- Xiaopeng Li (graduate student), selected as the sole theory JQI Postdoc Fellow in the competition of over 150 applicants in the year of 2013, Univ of Maryland, College Park. Fellowship from Oct 2013 -2016.
- Xiaopeng Li (graduate student), Graduate Fellowship of KITP (Kavli Institute for Theoretical Physics), UC Santa Barbara, Spring term 2013.
- Xiaopeng Li (graduate student), A. W. Mellon Fellowship of the University of Pittsburgh, 2012-2013
- Xiaopeng Li (graduate student), A. W. Mellon Fellowship of the University of Pittsburgh, 2011-2012

4.8 Scientific Services, Organized Conferences, etc. (by PI)

- **KITPC Conference** "Synthetic Topological Quantum Matter", August 1-5, 2016, Kavli Institute for Theoretical Physics China, Beijing, China.
  Advisory Committee: W. Vincent Liu, Ian Spielman
  International Coordinators: Gediminas Juzeliunas, Wu-Ming Liu, Xiong-Jun Liu, Boris A. Malomed, Han Pu, Su Yi, Chuanwei Zhang
  http://www.kitpc.ac.cn/?p=ProgDetail&id=CS20160801&i=main

- **KITPC Program** "Spin-orbital coupled quantum gases", August 1-19, 2016, Kavli Institute for Theoretical Physics China, Beijing, China.
  Advisory Committee: W. Vincent Liu, Ian Spielman
  International Coordinators: Gediminas Juzeliunas, Wu-Ming Liu, Xiong-Jun Liu, Boris A. Malomed, Han Pu, Su Yi, Chuanwei Zhang
  http://www.kitpc.ac.cn/?p=ProgDetail&id=PS20160801&i=main

- Summer Workshop on "Beyond Standard Quantum Gases", Qin Emperor Island City, China, Aug 5-7, 2016.
  Hosts: W. Vincent LIU (University of Pittsburgh), Linghua WEN (Yanshan University), Biao WU (Peking University)
  http://quantumsea.wikispaces.com

- Co-organizer, KITPC Symposium "Precision Tests of Many-Body Physics with Ultracold Quantum Gases" , June 9-13, 2014, Kavli Institute for Theoretical Physics China, Beijing, China.
  http://www.kitpc.ac.cn/?p=ProgDetail&id=CP20140609&i=main

- Co-organizer, Pitt Quantum Initiative (PQI) Symposium on "Quantum Matter", 18-19 April 2013, University of Pittsburgh. http://pqi.pitt.edu/events

- Co-organizer, Symposium on "Novel Topological Quantum Matter", February 25-26, 2013, University of Texas at Dallas campus, sponsored by U.S. Army Research Office (ARO)
  http://www.utdallas.edu/nsm/quantum/index.html

- Member of National Advisory Board, Kavli Institute for Theoretical Physic s China (KITPC), Chinese Academy of Sciences, Beijing, China, 2011–2016

5 Collaborative Research

5.1 People in PI's group during the reporting period

Graduate students:
(a) Zehan Li (2015–)

(b) Xiaopeng Li (PhD 2013). Mellon predoctoral fellowship, twice, 2010-11 and 2011-12. Selected as KITP Santa Barbara Graduate Fellow for Spring 2013 by nomination. Invited speaker for 2013 APS March Meeting. Now JQI Postdoc Fellow in U of Maryland since Oct 2013.)

(c) Zixu Zhang (PhD, 2012), now physicist in finance, Morgan-Stanley.

Exchange and Other Students

(d) Lijun LANG (exchange student from Institute of Physics, Chinese Academy of Sciences, Beijing, China. At Pitt 2013-2014)

(e) Jin-Long YU (exchange student from Tsinghua University, China. At Pitt Feb -July, 2013)

Postdocs

(a) Biao Huang (PhD, Ohio State University, 2016), Sep 2016 –

(b) Ahmet Keles (PhD, Univ of Washington Seattle, 2014), joint postdoc with Prof. Erhai Zhao/George Mason U, Sep 2014 –

(c) Haiyuan Zou (PhD. Univ of Iowa, 2014), Aug 2014 –

(d) Bo Liu (PhD, Peking University, 2013), January 2013 –August 2016. After training in Pitt, became Full Professor in Xi'An Jiao Tong University, China.

(e) Maksims Arzamasovs (PhD, University of Birmingham , 2014), Nov 2014 –Mar 2017

(f) Zhifang Xu (PhD, Tsinghua U, 2009), Nov 2013 – Apr 2015. Then became Full Professor of Physics, in Huazhong University of Science and Technology, Wuhan, China.

(g) Zhenyu Zhou (PhD, Washington U St Louis, 2013), joint postdoc with Prof. Erhai Zhao/George Mason U, Sep 2013 – May 2015.

5.2 Collaborations

PI's group had collaborations during the reporting period with:

- Leon Balents (Kavli Institute for Theoretical Physics (KITP), UC Santa Barbara)
- M. T. Batchelor (Australian National University)
- S. Das Sarma (Univ of Maryland)
- I. H. Deutsch and K. Goyal (University of New Mexico)
- X.-W. Guan (Australian National University)

- P. Hauke (ICFO-Institut de Ciències Fotòniques, Spain)
- A. Hemmerich (University of Hamburg)
- C. Ho (UC Berkeley; now at Vanderbilt University)
- H.-H. Hung (UCSD)
- Y. B. Kim (Univ of Toronto, Canada)
- M. Lewenstein (ICFO-Institut de Ciències Fotòniques, Spain)
- Xiongjun LIU (MIT and Hong University of Science and Tech)
- J. Moore (UC Berkeley)
- Arun Paramekanti (U of Toronto)
- M. Oshikawa (U of Tokoyo)
- V. M. Stojanovic (Carnegie Mellon Univ)
- K. Sun (postdoc at Joint Quantum Institute, U of Maryland)
- Biao WU (Peking University, Beijing, China)
- Erhai Zhao (George Mason University, Fairfax, VA)
- Peter Zoller (University of Innsbruck)

5.3 Supported Visitors and Participants

The following visitors were supported in part or full by the ARO grant during their extended visits:

1. Ahmet Keles (postdoc from George Mason University, Fairfax, VA), visited Pittsburgh 1 month (approximate), May 11- June 14, 2015
2. Xuguang YUE (postdoc from Zhejiang University of Technology, Hangzhou, China), visited Pittsburgh 3 months (approximate), March 30 - June 29, 2014
3. Jan 12-15, 2013, Matthias Troyer (ETH Zürich). Seminar on Jan 13, 2014: "Quantum Annealing and the D-Wave devices"
4. Jan 12-18, 2014, Peter Zoller (University Innsbruck). Informal Blackboard Talk: "New Frontiers of Quantum Simulations with Atoms and Ions", Jan 16, 2014

5. Feb 6- March 6, 2014, Xiongjun Liu (HKUST and MIT), Seminar 1 (Feb 13 Thursday 4:30 pm): “Manipulating Majorana Zero Modes in Chiral and Time-reversal Invariant Quantum Nanowires”;

   Seminar 2 (Informal discussion, Feb 18, Tuesday 7:00 pm): “Exploring Topological Phases with Cold Atoms”

6. Apr 2-4, 2014, Dmitri Feldman (Brown University), extended visit and informal discussion after department seminar.

7. Apr 13-14, Leon Balents (University of California at Santa Barbara), extended visit and informal discussion after colloquium.

8. April 15-18, Chuanwei Zhang (University of Texas at Dallas), Seminar (Apr 17, Thursday): “Search for Majorana Fermions in Spin-Orbit Coupled Superfluids and Superconductors”

9. April 8-15, Xiaopeng LI (University of Maryland). Li is a former student of the group. Dr. Li’s extended visit overlapped with Leon Balents’ visit, for a joint collaboration on orbital physics in electronic oxides. See [25] and its selection by Nature Nanotech as “highlight”.

10. Dr. Kush Saha, Department of Theoretical Physics, Indian Association for the Cultivation of Science, Kolkata, India. Informal seminar/teleconference: “Interacting bosons in an optical lattice in the presence of a synthetic gauge potential”, Jan 13, 2013

11. Dr. Tyler Dodds, University of Toronto, informal talk/teleconference: “Quantum spin liquids in the absence of spin rotation symmetry: An application to Herbertsmithite”, Jan 14, 2013

12. Dr. Huazhou Wei, University of California, Riverside, informal talk/teleconference: "Excitonic Phases from Weyl Semi-Metals", Jan 16, 2013

13. Mr. Zhenyu Zhou, Washington University in St. Louis, informal talk/teleconference: “Heat equation approach to geometric changes of the torus Laughlin-state”, Jan 22, 2013

14. Professor Andreas Hemmerich (University of Hamburg, Germany), visit period: March 20-23, 2013. Seminar: “New physics in unconventional optical lattices”, March 21, 2013.

15. Professor Ziqiang WANG (Boston College), visit period April 14-16, 2013. Talk: “Physics of electron correlation in materials containing transition metals”, Monday April 15, 2013.

16. Professor Kai Sun (U of Michigan Ann Arbor), visit period April 22-25, 2013. Pizza Lunch seminar: “Adiabatic continuity between Hofstadter and Chern insulator states”, April 23, 2013, Tuesday 12:00pm-1:00pm

17. Prof. Zohar Nussinov (Washington University, St Louis), visit: March 21-24, 2012. Pizza Lunch Seminar: “The detection of hidden spatial and spatio-temporal structures in complex physical systems by multi-scale clustering and some of their properties" on March 23, 2012.

18. Prof. David Weiss, Penn State University, March 19-20, 2012. Lecture: Informal discussion on "Experiments with Atoms in Optical Lattices", March 20.

19. Mr. Hannes Pichler (PhD student, University of Innsbruck), visit: the week of April 17. Informal discussion: “Many-body dynamics of cold atoms in noisy optical lattices” April 17, 2012.

20. Dr. Adrian Kantian (postdoc, University of Geneva), Visit period: March 5-8, 2012. Lecture in joint Liu-Daley group meeting: “Mobile impurities in 1D cold gases” on Tuesday March 6.

21. Dr. Ulf Bissbort (postdoc, University of Frankfurt), visit period: March 6-9. Pizza Lunch Seminar: “Quasi-particle theory and dynamics of strongly interacting bosons in optical lattices,” on Mar 7, Wednesday.

6 Publications in the reporting period

[1] X. Li and W. V. Liu, "Physics of higher orbital bands in optical lattices: a review," *Rep. Prog. Phys.* **79** (2016), no. 11, 116401.

[2] M. Lewenstein and W. V. Liu, "Optical lattices: Orbital dance," *Nature Physics* **7** (2011) 101.

[3] B. Huang, Y.-H. Wu, and W. V. Liu, "Clean Floquet Time Crystals: Models and Realizations in Cold Atoms," 2017. arXiv:1703.04663.

[4] Z.-F. Xu, L. You, A. Hemmerich, and W. V. Liu, "π-flux dirac bosons and topological edge excitations in a bosonic chiral p-wave superfluid," *Phys. Rev. Lett.* **117** (Aug, 2016) 085301.

[5] X. Li, E. Zhao, and W. V. Liu, "Effective action approach to the p-band mott insulator and superfluid transition," *Phys. Rev. A* **83** (Jun, 2011) 063626.

[6] X. Li, A. Paramekanti, A. Hemmerich, and W. V. Liu, "Proposed formation and dynamical signature of a chiral Bose liquid in an optical lattice," *Nat. Commun.* **5** (2014) 3205.

[7] Y. Xu, Z. Chen, H. Xiong, W. V. Liu, and B. Wu, "Stability of p-orbital Bose-Einstein condensates in optical checkerboard and square lattices," *Phys. Rev. A* **87** (2013) 013635.

[8] X. Li, Z. Zhang, and W. V. Liu, "Time-reversal symmetry breaking of p-orbital bosons in a one-dimensional optical lattice," *Phys. Rev. Lett.* **108** (2012) 175302.

[9] A. Keleş, E. Zhao, and W. V. Liu, "Effective theory of interacting fermions in shaken square optical lattices," *Phys. Rev. A* **95** (Jun, 2017) 063619.

[10] B. Liu, X. Li, R. G. Hulet, and W. V. Liu, "Detecting π-phase superfluids with p-wave symmetry in a quasi-one-dimensional optical lattice," *Phys. Rev. A* **94** (Sep, 2016) 031602.

[11] Z. Zhou, E. Zhao, and W. V. Liu, "Spin-orbital exchange of strongly interacting fermions in the p band of a two-dimensional optical lattice," *Phys. Rev. Lett.* **114** (Mar, 2015) 100406.

[12] Z. Zhang, X. Li, and W. V. Liu, "Stripe, checkerboard, and liquid-crystal ordering from anisotropic p-orbital Fermi surfaces in optical lattices," *Phys. Rev. A* **85** (May, 2012) 053606.

[13] P. Hauke, E. Zhao, K. Goyal, I. H. Deutsch, W. V. Liu, and M. Lewenstein, "Orbital order of spinless fermions near an optical Feshbach resonance," *Phys. Rev. A* **84** (2011) 051603.

[14] Z.-F. Xu, X. Li, P. Zoller, and W. V. Liu, "Spontaneous quantum Hall effect in an atomic spinor Bose-Fermi mixture," *Phys. Rev. Lett.* **114** (Mar, 2015) 125303.

[15] B. Liu, X. Li, and W. V. Liu, "Topological phases via engineered orbital hybridization in noncentrosymmetric optical lattices," *Phys. Rev. A* **93** (Mar, 2016) 033643.

[16] X.-J. Liu, Z.-X. Liu, K. T. Law, W. V. Liu, and T. K. Ng, "Chiral topological orders in an optical raman lattice," *New J. Phys.* **18** (2016), no. 3, 035004.

[17] B. Liu, X. Li, B. Wu, and W. V. Liu, "Chiral superfluidity with p-wave symmetry from an interacting s-wave atomic Fermi gas," *Nat. Commun.* **5** (Sep, 2014) 5064.

[18] X. Li, E. Zhao, and W. V. Liu, "Topological states in a ladder-like optical lattice containing ultracold atoms in higher orbital bands," *Nat. Commun.* **4** (2013) 1523.

[19] X. Li and W. V. Liu, "Orbital coupled dipolar fermions in an asymmetric optical ladder," *Phys. Rev. A* **87** (2013) 063605.

[20] K. Sun, W. V. Liu, A. Hemmerich, and S. D. Sarma, "Topological semimetal in a fermionic optical lattice," *Nat. Phys.* **8** (2012) 67.

[21] H. Zou, E. Zhao, and W. V. Liu, "Frustrated magnetism of dipolar molecules on a square optical lattice: Prediction of a quantum paramagnetic ground state," *Phys. Rev. Lett.* **119** (Jul, 2017) 050401.

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