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RPPR Final Report
as of 26-Jan-2023

Agency Code: 21XD

Proposal Number: 68647PE

Agreement Number: W911NF-17-1-0128

INVESTIGATOR(S):

Name: Chuanwei Zhang
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Report Date: 14-Feb-2023

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Final Report for Period Beginning 15-Mar-2017 and Ending 14-Nov-2022

Title: Quantum Phases and Dynamics of Periodically Driven Ultra-Cold Atomic Gases - Atomic and Molecular Physics Program (6.3)

Begin Performance Period: 15-Mar-2017

End Performance Period: 14-Nov-2022

Report Term: 0-Other

Submitted By: Chuanwei Zhang

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STEM Degrees: 2

STEM Participants: 9

Major Goals: Ultra-cold atomic gases provide a clean and highly controllable platform for emulating many-body phenomena and engineering new quantum materials. In cold atomic gases, external potentials can be induced periodically not only in the real space (i.e., optical lattices), but also in the time domain. Such periodic modulation of the system Hamiltonian, together with some recently developed experimental tools such as spin-orbit coupling, open a broad avenue for discovering new quantum matter. In this project, we utilize various experimental tools with the periodic driving of system parameters for engineering new many-body quantum matters and exploring their non-equilibrium dynamics in cold atomic gases. Our proposed research contains both fast time modulation for Floquet quantum matter and adiabatic modulation for topological transport of cold atoms. We also explore novel quantum phases and dynamics in time-dependence potentials. Our theoretical efforts will be closely coupled to ongoing experimental efforts at Washington State University, Purdue University, UIUC, and University of Washington.

Accomplishments: See the attached file

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Training Opportunities: Research is a crucial part of science education at both graduate and undergraduate levels, and the involvement of students in research activities is an integral part of the proposed work. In the summers of 2018-2022, the PI hosted four REU students: Xingyi Wang (female) from Reed College (2018), Owen Tower (male) from University of Massachusetts at Dartmouth (2019), Quincy Webb (female) from Smith College (2020), and Luke Elder (male) from Roanoke College (2022). Xingyi worked with the PI and graduate student Junpeng Hou on a project about superstripe phases in a spin-orbit coupled Bose-Einstein condensate. Owen and Quincy worked with the PI, Prof. Kolodrubetz, and Junpeng Hou on a project about statistical quantum information processing. Luke worked with the PI on the quantum dynamics and phases in a non-Hermitian system.

The PI supervised six physics graduate students Matthew Maisberger, Mohammad M Mahmud, Junpeng Hou, Mengxin Du, Samyak Shrestha, and Arunaday Gupta during the grant period. Matthew Maisberger received his PhD in Dec 2020 and joined J. P. Morgan Chase as a Data Scientist. Junpeng Hou received his PhD in August 2021 and joined Facebook research as a research scientist. Mengxin has made important progress toward his PhD thesis. Samyak and Arunaday just started. The PI has supervised them on a daily basis to accomplish these projects. The synergistic combination of various numerical and analytic techniques in the proposed research promotes the interaction between students and the PI as well as the postdoctoral research associates in the group. As part of their training, students have presented their work at department seminars and major scientific conferences (e.g., APS March meeting and DAMOP meeting) to develop their communication skills. My former PhD student, Chunlei Qu (PhD 2015), joined Stevens Institute of Technology as an Assistant Professor in the Spring 2020.

Several postdoctoral research associates (Xiwang Luo, Ying Su, Haiping Hu, Yunmei Li) played an important role in some grant-related activities. They have helped the PI mentor graduate students on the daily basis, which is considered as a part of their training so that they are familiar with the student mentoring process after they become independent faculty in the future. The PI's mentorship to postdoctoral associates focuses on the development of their independent research projects, effective scientific presentations (both oral and written), broadening their research visions, etc.

The PI taught Quantum Mechanics II for graduate students in Spring 2019-2022 and Quantum Computing for undergraduate and graduate students in Fall 2018 and 2021. He also taught Quantum algorithm and software in Fall 2022. In addition to teaching physical principles in this course, the PI has made initial efforts to integrate state-of-art research related to course topics into lectures, with the purposes to enhance students' interest in AMO and condensed matter research and also to encourage them to undertake hands-on research. I worked with each student individually to pick an active research topic in condensed matter and cold atoms physics and develop some interesting research projects for them. All these activities expose the students to the frontier of cold atoms and condensed matter research and the students are very excited about that.

Results Dissemination: These research activities lead to 49 papers published in peer-reviewed journals, including 2 in Nature Physics, 4 in Nature Communications, 1 in Physical Review X and 13 in Physical Review Letters. Three papers have been selected as Editors' suggestions by editors of Physical Review Letters and Physical Review Research. Our work on superfluid quasicrystals has been widely reported by various news media, including Newsweek magazine.

Honors and Awards: In October 2017, the PI was elected to the Fellow of American Physical Society, with the citation: "For seminal contributions to theoretical research in ultracold atomic physics, including studies of spin-orbit coupled quantum gases, topological superfluids with Majorana or Weyl fermions, and Fulde-Ferrell superfluid states." The cited works have been supported by ARO in the past.

In 2022, my student Junpeng Hou's PhD thesis received the President David Daniel Dissertation award, the highest award for UTD PhD students.

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

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Participant: Xiwang Luo

Person Months Worked: 15.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Yunmei Li

Person Months Worked: 6.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Haiping Hu

Person Months Worked: 12.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Ying Su

Person Months Worked: 7.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Junpeng Hou

Person Months Worked: 13.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Other (specify)

Participant: Yajie Wu

Person Months Worked: 3.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Other (specify)

Participant: Lichen Zhao

Person Months Worked: 3.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Other (specify)

Participant: Xiaofan Zhou

Person Months Worked: 6.00

Funding Support:

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Project Contribution:
National Academy Member: N

Participant Type: PD/PI
Participant: Chuanwei Zhang
Person Months Worked: 10.00
Project Contribution:
National Academy Member: N

Funding Support:

International Collaboration:

CHN

JPN
JPN

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Volume: 95

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Date Submitted: 8/29/17 12:00AM

Date Published: 4/1/17 5:00AM

Publication Location:

Article Title: Stueckelberg interferometry using periodically driven spin-orbit-coupled Bose-Einstein condensates

Authors: Abraham J. Olson, David B. Blasing, Chunlei Qu, Chuan-Hsun Li, Robert J. Niffenegger, Chuanwei Zhang

Keywords: spin-orbit, Floquet, periodic modulation, BEC

Abstract: We study the single-particle dispersion of a spin-orbit-coupled (SOC) Bose-Einstein condensate (BEC) under the periodical modulation of the Raman coupling. This modulation introduces a further coupling of the SOC dressed eigenlevels, thus creating a second generation of modulation-dressed eigenlevels. Theoretical calculations show that these modulation-dressed eigenlevels feature a pair of avoided crossings and a richer spin-momentum locking, which we observe using BEC transport measurements. Furthermore, we use the pair of avoided crossings to engineer a tunable Stueckelberg interferometer that gives interference fringes in the spin polarization of BECs.

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Acknowledged Federal Support: Y

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Nature Communications

Publication Identifier Type: DOI

Publication Identifier: 10.1038/ncomms16097

Volume: 8

Issue:

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Date Submitted: 8/29/17 12:00AM

Date Published: 7/1/17 5:00AM

Publication Location:

Article Title: Synthetic-lattice enabled all-optical devices based on orbital angular momentum of light

Authors: Xi-Wang Luo, Xingxiang Zhou, Jin-Shi Xu, Chuan-Feng Li, Guang-Can Guo, Chuanwei Zhang, Zheng-V

Keywords: photon, OAM, cavity

Abstract: All-optical photonic devices are crucial for many important photonic technologies and applications, ranging from optical communication to quantum information processing. Conventional design of all-optical devices is based on photon propagation and interference in real space, which may rely on large numbers of optical elements, and the requirement of precise control makes this approach challenging. Here we propose an unconventional route for engineering all-optical devices using the photon's internal degrees of freedom, which form photonic crystals in such synthetic dimensions for photon propagation and interference. We demonstrate this design concept by showing how important optical devices such as quantum memory and optical filters can be realized using synthetic orbital angular momentum (OAM) lattices in degenerate cavities. The design route utilizing synthetic photonic lattices may significantly reduce the requirement for numerous optical elements and their fine tuning in convention

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

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Volume: 96

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Article Title: Adiabatically tuning quantized supercurrents in an annular Bose-Einstein condensate

Authors: Junpeng Hou, Xi-Wang Luo, Kuei Sun, Chuanwei Zhang

Keywords: adiabatic, spin-orbit-angular-momentum coupling, supercurrent

Abstract: The ability to generate and tune quantized persistent supercurrents is crucial for building superconducting or atomtronic devices with novel functionalities. In ultracold atoms, previous methods for generating quantized supercurrents are generally based on dynamical processes to prepare atoms in metastable excited states. Here, we show that arbitrary quantized circulation states can be adiabatically prepared and tuned as the ground state of a ring-shaped Bose-Einstein condensate by utilizing spin-orbital-angular-momentum (SOAM) coupling and an external potential. There exists superfluid hysteresis for tuning supercurrents between different quantization values with nonlinear atomic interactions, which is explained by developing a nonlinear Landau-Zener theory. Our work will provide a powerful platform for studying SOAM-coupled ultracold atomic gases and building atomtronic circuits.

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

Journal: Physical Review A

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Date Submitted: 10/3/18 12:00AM

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Article Title: Observation of Floquet band change in driven ultracold Fermi gases

Authors: Lianghui Huang, Peng Peng, Donghao Li, Zengming Meng, Liangchao Chen, Chunlei Qu, Pengjun Wan

Keywords: topological, Floquet, spin-orbit coupling, Dirac point

Abstract: Periodic driving of a quantum system can significantly alter its energy bands and even change the band topology, opening a completely new avenue for engineering novel quantum matter. Although important progress has been made recently in measuring topological properties of Floquet bands in different systems, direct experimental measurement of Floquet band dispersions and their topology change is still demanding. Here we directly measure Floquet band dispersions in a periodically driven spin-orbit coupled ultracold Fermi gas. Using spin injection radio-frequency spectroscopy, we observe that the Dirac point originating from two dimensional spin-orbit coupling can be manipulated to emerge at the lowest or highest two dressed bands by fast modulating Raman laser frequencies, demonstrating topological change of Floquet bands. Our work will provide a powerful tool for understanding fundamental Floquet physics as well as engineering exotic topological quantum matter.

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Volume: 119 **Issue:** **First Page #:** 193001
Date Submitted: 10/3/18 12:00AM **Date Published:**
Publication Location:

Article Title: Spin-tensor--momentum-coupled Bose-Einstein condensates

Authors: Xi-Wang Luo, Kuei Sun, Chuanwei Zhang

Keywords: spin-tensor, spin-orbit coupling, BEC, supersolid

Abstract: The recent experimental realization of spin-orbit coupling for ultracold atomic gases provides a powerful platform for exploring many interesting quantum phenomena. In these studies, spin represents spin vector (spin-1/2 or spin-1) and orbit represents linear momentum. Here we propose a scheme to realize a new type of spin-tensor--momentum coupling (STMC) in spin-1 ultracold atomic gases. We study the ground state properties of interacting Bose-Einstein condensates (BECs) with STMC and find interesting new types of stripe superfluid phases and multicritical points for phase transitions. Furthermore, we show that a stripe phase with a long tunable period and high visibility of density modulation can be dynamically generated using STMC, paving the way for direct experimental observation of the long-sought stripe phases. Our scheme for generating STMC can be generalized to other systems and may open the door for exploring novel quantum physics and device applications.

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Volume: 97 **Issue:** **First Page #:** 043841
Date Submitted: 10/3/18 12:00AM **Date Published:** 4/17/18 5:00AM
Publication Location:

Article Title: Topological photonic orbital angular momentum switch

Authors: Xi-Wang Luo, Chuanwei Zhang, Guang-Can Guo, Zheng-Wei Zhou

Keywords: topological pumping, photonic OAM

Abstract: The large number of available orbital angular momentum (OAM) states of photons provides a unique resource for many important applications in quantum information and optical communications. However, conventional OAM switching devices usually rely on precise parameter control and are limited by slow switching rate and low efficiency. Here we propose a robust, fast and efficient photonic OAM switch device based on a topological process, where photons are adiabatically pumped to a target OAM state on demand. Such topological OAM pumping can be realized through manipulating photons in a few degenerate main cavities and involves only a limited number of optical elements. A large change of OAM at $\sim 10q$ can be realized with only q degenerate main cavities and at most $5q$ pumping cycles. The topological photonic OAM switch may become a powerful device for broad applications in many different fields.

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Date Submitted: 10/3/18 12:00AM **Date Published:** 11/1/17 5:00AM
Publication Location:

Article Title: Spin-orbit-driven transitions between Mott insulators and finite-momentum superfluids of bosons in optical lattices

Authors: Mi Yan, Yinyin Qian, Hoi-Yin Hui, Ming Gong, Chuanwei Zhang, V. W. Scarola

Keywords: spin-orbit coupling, cold atoms

Abstract: Synthetic spin-orbit coupling in ultracold atomic gases can be taken to extremes rarely found in solids. We study a two-dimensional Hubbard model of bosons in an optical lattice in the presence of spin-orbit coupling strong enough to drive direct transitions from Mott insulators to superfluids. Here we find phase-modulated superfluids with finite momentum that are generated entirely by spin-orbit coupling. We investigate the rich phase patterns of the superfluids, which may be directly probed using time-of-flight imaging of the spin-dependent momentum distribution.

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Volume: 5 **Issue:** 1 **First Page #:** 011005
Date Submitted: 10/3/18 12:00AM **Date Published:** 11/1/17 5:00AM
Publication Location:

Article Title: Valley-selective topologically ordered states in irradiated bilayer graphene

Authors: Chunlei Qu, Chuanwei Zhang, Fan Zhang

Keywords: valley, graphene

Abstract: Gapless bilayer graphene is susceptible to a variety of spontaneously gapped states. As predicted by theory and observed by experiment, the ground state is, however, topologically trivial, because a valley-independent gap is energetically favorable. Here, we show that under the application of interlayer electric field and circularly polarized light, one valley can be selected to exhibit the original interaction instability while the other is frozen out. Tuning this Floquet system stabilizes multiple competing topologically ordered states, distinguishable by edge transport and circular dichroism. Notably, quantized charge, spin, and valley Hall conductivities coexist in one stabilized state.

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Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevLett.120.060407
Volume: 120 **Issue:** 6 **First Page #:**
Date Submitted: 10/3/18 12:00AM **Date Published:** 2/1/18 6:00AM
Publication Location:

Article Title: Superfluid-Quasicrystal in a Bose-Einstein Condensate

Authors: Junpeng Hou, Haiping Hu, Kuei Sun, Chuanwei Zhang

Keywords: superfluid quasicrystal

Abstract: A quasicrystal is a class of ordered structures defying conventional classification of solid crystals and may carry classically forbidden (e.g., fivefold) rotational symmetries. In view of long-sought supersolids, a natural question is whether a superfluid can spontaneously form quasicrystalline order that is not possessed by the underlying Hamiltonian, forming “superfluid-quasicrystals.” Here we show that a superfluidquasicrystal stripe state with the minimal fivefold rotational symmetry can be realized as the ground state of a Bose-Einstein condensate within a practical experimental scheme. There exists a rich phase diagram consisting of various superfluid-quasicrystal, supersolid, and plane-wave phases. Our scheme can be generalized for generating other higher-order (e.g., sevenfold) quasicrystal states, and provides a platform for investigating such new exotic quantum matter.

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Journal: Physical Review Letters
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevLett.120.120401
Volume: 120 **Issue:** 12 **First Page #:**
Date Submitted: 10/3/18 12:00AM **Date Published:** 3/1/18 12:00AM
Publication Location:

Article Title: Momentum-Space Josephson Effects

Authors: Junpeng Hou, Xi-Wang Luo, Kuei Sun, Thomas Bersano, Vandna Gokhroo, Sean Mossman, Peter Eng

Keywords: Momentum space Josephson BEC

Abstract: The Josephson effect is a prominent phenomenon of quantum supercurrents that has been widely studied in superconductors and superfluids. Typical Josephson junctions consist of two real-space superconductors (superfluids) coupled through a weak tunneling barrier. Here we propose a momentum-space Josephson junction in a spin-orbit coupled Bose-Einstein condensate, where states with two different momenta are coupled through Raman-assisted tunneling. We show that Josephson currents can be induced not only by applying the equivalent of “voltages,” but also by tuning tunneling phases. Such tunneling-phase-driven Josephson junctions in momentum space are characterized through both full mean field analysis and a concise two-level model, demonstrating the important role of interactions between atoms. Our scheme provides a platform for experimentally realizing momentum-space Josephson junctions and exploring their applications in quantum-mechanical circuits.

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Date Submitted: 10/3/18 12:00AM

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Article Title: Time-reversal-invariant spin-orbit-coupled bilayer Bose-Einstein condensates

Authors: Matthew Maisberger, Lin-Cheng Wang, Kuei Sun, Yong Xu, Chuanwei Zhang

Keywords: spin-orbit coupling, cold atoms

Abstract: Time-reversal invariance plays a crucial role for many exotic quantum phases, particularly for topologically nontrivial states, in spin-orbit coupled electronic systems. Recently realized spin-orbit coupled cold-atom systems, however, lack the time-reversal symmetry due to the inevitable presence of an effective transverse Zeeman field. We address this issue by analyzing a realistic scheme to preserve time-reversal symmetry in spin-orbit-coupled ultracold atoms, with the use of Hermite-Gaussian-laser-induced Raman transitions that preserve spin-layer time-reversal symmetry. We find that the system's quantum states form Kramers pairs, resulting in symmetry-protected gap closing of the lowest two bands at arbitrarily large Raman coupling. We also show that Bose gases in this setup exhibit interaction-induced layer-stripe and uniform phases as well as intriguing spin-layer symmetry and spin-layer correlation.

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Article Title: Topological Triply Degenerate Points Induced by Spin-Tensor-Momentum Couplings

Authors: Haiping Hu, Junpeng Hou, Fan Zhang, Chuanwei Zhang

Keywords: triply-degenerate point, spin-tensor

Abstract: The recent discovery of triply degenerate points (TDPs) in topological materials has opened a new perspective toward the realization of novel quasiparticles without counterparts in quantum field theory. The emergence of such protected nodes is often attributed to spin-vector-momentum couplings. We show that the interplay between spin-tensor- and spin-vector-momentum couplings can induce three types of TDPs, classified by different monopole charges ($C \frac{1}{4} 2, 1, 0$). A Zeeman field can lift them into Weyl points with distinct numbers and charges. Different TDPs of the same type are connected by intriguing Fermi arcs at surfaces, and transitions between different types are accompanied by level crossings along high-symmetry lines. We further propose an experimental scheme to realize such TDPs in cold-atom optical lattices. Our results provide a framework for studying spin-tensor-momentum coupling-induced TDPs and other exotic quasiparticles.

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Article Title: Self-Adapted Floquet Dynamics of Ultracold Bosons in a Cavity

Authors: Xi-Wang Luo, Chuanwei Zhang

Keywords: Floquet, Bosons, Cavity

Abstract: Floquet dynamics of a quantum system subject to periodic modulations of system parameters provides a powerful tool for engineering new quantum matter with exotic properties. While system dynamics is significantly altered, the periodic modulation itself is usually induced externally and independent of Floquet dynamics. Here we propose a new type of Floquet physics for a Bose-Einstein condensate (BEC) subject to a shaken lattice generated inside a cavity, where the shaken lattice and atomic Floquet bands are mutually dependent, resulting in self-adapted Floquet dynamics. In particular, the shaken lattice induces Floquet quasienergy bands for the BEC, whose backaction leads to a self-adapted dynamical normal-superradiant phase transition for the shaken lattice. Such self-adapted Floquet dynamics shows two surprising and unique features: (i) The normal-superradiant phase transition possesses a hysteresis even without atom interactions. (ii) The dynamical atom-cavity steady state could exist

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Article Title: Spin-1 topological monopoles in the parameter space of ultracold atoms

Authors: Haiping Hu, Chuanwei Zhang

Keywords: spin-1 monopole, cold atoms, parameter space

Abstract: A magnetic monopole is a hypothetical elementary particle with an isolated magnetic pole. Its existence would directly lead to the quantization of electric charges. In recent years, analogs of magnetic monopoles, represented by topological defects in parameter spaces, have been studied in a wide range of physical systems. These works mainly focused on Abelian Dirac monopoles in spin-1/2 or non-Abelian Yang monopoles in spin-3/2 systems. Here we propose to realize three types of spin-1 topological monopoles and study their geometric properties using the parameter space formed by three hyperfine states of ultracold atoms coupled by radio-frequency fields. These spin-1 monopoles, characterized by different monopole charges, possess distinct Berry curvature fields and spin textures, which are directly measurable in experiments. The topological phase transitions between different monopoles are accompanied by the emergence of a spin "vortex" and can be intuitively visualized using Majorana's

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Article Title: Momentum space Aharonov-Bohm interferometry in Rashba spin-orbit coupled Bose-Einstein condensates

Authors: Junpeng Hou, Xi-Wang Luo, Kuei Sun, Chuanwei Zhang

Keywords: Aharonov-Bohm interferometry, BEC

Abstract: The recent experimental realization of synthetic Rashba spin-orbit coupling (SOC) paves a new avenue for exploring topological phases in ultracold atoms. The unequivocal characterization of such topological physics requires a simple scheme for measuring the Berry phase originating from the SOC. Here we propose a scheme to realize momentum space Aharonov-Bohm interferometry in a Rashba spin-orbit-coupled Bose-Einstein condensate through a sudden change of the in-plane Zeeman field. We find that the π Berry phase for the Dirac point of the Rashba SOC is directly revealed by a robust dark interference fringe in the momentum space. An external perpendicular Zeeman field opens a band gap at the Dirac point, which reduces the Berry phase along the Rashba ring, leading to lower brightness of the interference fringe. We develop a variational model with semiclassical equations of motion of essential dynamical quantities for describing the interference process, yielding real and momentum space t

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Publication Location:

Article Title: Majorana Doublets, Flat Bands, and Dirac Nodes in

Authors: Haiping Hu, Fan Zhang, Chuanwei Zhang

Keywords: Majorana fermion, spin-orbit coupling, cold atoms

Abstract: Topological superfluids protected by mirror and time-reversal symmetries are exotic states of matter possessing Majorana Kramers pairs (MKPs), yet their realizations have long been hindered by the requirement of unconventional pairing. We propose to realize such a topological superfluid by utilizing s-wave pairing and emergent mirror and time-reversal symmetries in two coupled 1D ultracold atomic Fermi gases with spin-orbit coupling. By stacking such systems into 2D, we discover topological and Dirac-nodal superfluids hosting distinct MKP flat bands. We show that the emergent symmetries make the MKPs and their flat bands stable against pairing fluctuations that otherwise annihilate Majorana pairs. Exploiting new experimental developments, our scheme provides a unique platform for exploring MKPs and their applications in quantum computation.

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Article Title: Spin current generation and relaxation in a quenched spin-orbit-coupled Bose-Einstein condensate

Authors: Chuan-Hsun Li, Chunlei Qu, Robert J. Niffenegger, Su-Ju Wang, Mingyuan He, David B. Blasing, Abrah

Keywords: spin current relaxation, spin-orbit, BEC

Abstract: Understanding the effects of spin-orbit coupling (SOC) and many-body interactions on spin transport is important in condensed matter physics and spintronics. This topic has been intensively studied for spin carriers such as electrons but barely explored for charge-neutral bosonic quasiparticles (including their condensates), which hold promises for coherent spin transport over macroscopic distances. Here, we explore the effects of synthetic SOC (induced by optical Raman coupling) and atomic interactions on the spin transport in an atomic Bose-Einstein condensate (BEC), where the spin-dipole mode (SDM, actuated by quenching the Raman coupling) of two interacting spin components constitutes an alternating spin current. We experimentally observe that SOC significantly enhances the SDM damping while reducing the thermalization (the reduction of the condensate fraction). We also observe generation of BEC collective excitations such as shape oscillations.

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Article Title: Experimental realization of a long-lived striped Bose-Einstein condensate induced by momentum-space hopping

Authors: Thomas M. Bersano, Junpeng Hou, Sean Mossman, Vandna Gokhroo, Xi-Wang Luo, Kuei Sun, Chuan

Keywords: stripe phase, spin-orbit, BEC

Abstract: The search for supersolidlike phases has attracted great attention in the fields of condensed matter and ultracold atom physics. Here, we experimentally demonstrate a route for realizing a superfluid stripe phase in a spin-orbit coupled Bose-Einstein condensate by employing a weak optical lattice to induce momentum-space hopping between two spin-orbit band minima. We characterize the striped ground state as a function of lattice coupling strength and spin-orbit detuning and find good agreement with mean-field simulations. We observe coherent Rabi oscillations in momentum space between two band minima and demonstrate a long lifetime of the ground state. Our work offers an exciting and stable experimental platform for exploring superfluid stripe phases and their exotic excitations, which may shed light on the properties of supersolidlike states.

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Article Title: Experimental realization of a non-magnetic one-way spin switch

Authors: Maren E. Mossman, Junpeng Hou, Xi-Wang Luo, Chuanwei Zhang, Peter Engels

Keywords: spin switch, one way, non-magnetic, spin-orbit, BEC

Abstract: Controlling magnetism through non-magnetic means is highly desirable for future electronic devices, as such means typically have ultra-low power requirements and can provide coherent control. In recent years, great experimental progress has been made in the field of electrical manipulation of magnetism in numerous material systems. These studies generally do not consider the directionality of the applied non-magnetic potentials and/or magnetism switching. Here, we theoretically conceive and experimentally demonstrate a non-magnetic one-way spin switch device using a spin-orbit coupled Bose–Einstein condensate subjected to a moving spin-independent repulsive dipole potential. The physical foundation of this unidirectional device is based on the breakdown of Galilean invariance in the presence of spin-orbit coupling. Such a one-way spin switch opens an avenue for designing quantum devices with unique functionalities and may facilitate further experimental investigations of other one-way

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Date Submitted: 8/25/19 12:00AM **Date Published:** 8/1/19 5:00AM
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Article Title: Majorana Corner Modes with Solitons in an Attractive Hubbard-Hofstadter Model of Cold Atom Optical Lattices

Authors: Chuanchang Zeng, T. D. Stanescu, Chuanwei Zhang, V. W. Scarola, Sumanta Tewari

Keywords: Corner mode, soliton

Abstract: Higher-order topological superconductors hosting Majorana-Kramers pairs (MKPs) 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.

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Article Title: Higher-Order Topological Corner States Induced by Gain and Loss

Authors: Xi-Wang Luo, Chuanwei Zhang

Keywords: higher-order corner mode, gain loss, topological insulator

Abstract: Higher-order topological insulators and superconductors are topological phases that exhibit novel boundary states on corners or hinges. Recent experimental advances in controlling dissipation such as gain and loss in atomic and optical systems provide a powerful tool for exploring non-Hermitian topological phases. Here we show that higher-order topological corner states can emerge by introducing staggered on-site gain and loss to a Hermitian system in a trivial phase. For such a non-Hermitian system, we establish a general bulk-corner correspondence by developing a biorthogonal nested-Wilson-loop and edge-polarization theory, which can be applied to a wide class of non-Hermitian systems with higher-order topological orders. The theory gives rise to topological invariants characterizing the non-Hermitian topological multipole moments (i.e., corner states) that are protected by reflection or chiral symmetry.

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Article Title: Topological Mott insulator with bosonic edge modes in one-dimensional fermionic superlattices

Authors: Haiping Hu, Shu Chen, Tian-Sheng Zeng, Chuanwei Zhang

Keywords: Topological Mott insulator, bosonic edge, superlattice

Abstract: We investigate topological phase transitions driven by interaction and identify a topological Mott insulator state in one-dimensional fermionic optical superlattices through a numerical density-matrix renormalization group method. Remarkably, the low-energy edge excitations change from spin-1/2 fermionic single-particle modes to spin-1 bosonic collective modes across the phase transition. Due to spin-charge separation, the low energy theory is governed by an effective spin superexchange model, whereas the charge degree of freedom is fully gapped out. Such topological Mott state can be characterized by a spin Chern number and gapless magnon modes protected by a finite spin gap. The proposed experimental setup is simple and may pave the way for the experimental observation of exotic topological Mott states.

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Article Title: Tunable spin-orbit coupling and magnetic superstripe phase in a Bose-Einstein condensate

Authors: Xi-Wang Luo, Chuanwei Zhang

Keywords: spin-orbit coupling, stripe phase, BEC

Abstract: Superstripe phases in Bose-Einstein condensates (BECs), possessing both crystalline structure and superfluidity, open a new avenue for exploring exotic quantum matters—supersolids. However, conclusive detection and further exploration of a superstripe is still challenging in experiments because of its short period, low visibility, fragility against magnetic-field fluctuation, or short lifetime. Here we propose a scheme in a spin-orbit coupled BEC which overcomes these obstacles and generates a robust magnetic superstripe phase, with only spin-density (no total density) modulation due to the magnetic translational symmetry, ready for direct real-space observation. In the scheme, two hyperfine spin states are individually Raman coupled with a largely detuned third state, which induce a momentum-space separation between two lower band dispersions, yielding an effective spin-1/2 system with tunable spin-orbit coupling and Zeeman fields. Without effective Zeeman fields, spin-dependent inte

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Article Title: Rashba and Weyl spin-orbit coupling in an optical lattice clock

Authors: Xiaofan Zhou, Xi-Wang Luo, Gang Chen, Suotang Jia, Chuanwei Zhang

Keywords: Rashba spin-orbit, atomic clock

Abstract: Recent experimental realization of one-dimensional spin-orbit coupling (SOC) for ultracold alkaline-earth(-like) atoms in optical lattice clocks opens a new avenue for exploring exotic quantum matter because of the strongly suppressed heating of atoms from lasers comparing with alkaline-earth atoms. Here we propose a scheme to realize two-dimensional (2D) Rashba and three-dimensional (3D) Weyl types of SOC in a 3D optical lattice clock and explore their topological phases. With 3D Weyl SOC, the system can support topological phases with various numbers as well as types (I or II) of Weyl points. The spin distributions of such topological bands for 2D Rashba and 3D Weyl SOC can be detected using suitably designed spectroscopic sequences. Our proposal may pave the way for the experimental realization of robust topological quantum matters and their exotic quasiparticle excitations in ultracold atomic gases.

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Article Title: Topological Bands and Triply Degenerate Points in Non-Hermitian Hyperbolic Metamaterials

Authors: Junpeng Hou, Zhitong Li, Xi-Wang Luo, Qing Gu, Chuanwei Zhang

Keywords: Non-Hermitian, photonics, hyperbolic

Abstract: Hyperbolic metamaterials (HMMs), an unusual class of electromagnetic metamaterials, have found important applications in various fields due to their distinctive properties. A surprising feature of HMMs is that even continuous HMMs can possess topological edge modes. However, previous studies based on equal-frequency surface (analogy of Fermi surface) may not correctly capture the topology of entire bands. Here we develop a topological band description for continuous HMMs that can be described by a non-Hermitian Hamiltonian formulated from Maxwell's equations. We find two types of three-dimensional non-Hermitian triply degenerate points with complex linear dispersions and topological charges ± 2 and 0 induced by chiral and gyromagnetic effects. Because of the photonic nature, the vacuum band plays an important role for topological edge states and bulk-edge correspondence in HMMs. The topological band results are numerically confirmed by direct simulation of Maxwell's equations.

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Article Title: Magnetic stripe soliton and localized stripe wave in spin-1 Bose-Einstein condensates

Authors: Li-Chen Zhao, Xi-Wang Luo, Chuanwei Zhang

Keywords: solitons, spin-tensor-momentum coupling, BEC

Abstract: The recent experimental realization of spin-orbit coupling for ultracold atomic gases opens a new avenue for engineering solitons with internal spatial structures through tuning atomic band dispersions. However, the types of the resulting stripe solitons in a spin-1/2 Bose-Einstein condensate (BEC) have been limited to dark-dark or bright-bright with the same density profiles for different spins. Here we propose that general types of stripe solitons, including magnetic stripe solitons (e.g., dark-bright) and localized stripe waves (neither bright nor dark), could be realized in a spin-1 BEC with widely tunable band dispersions through modulating the coupling between three spin states and the linear momentum of atoms. Surprisingly, a moving magnetic stripe soliton can possess both negative and positive effective masses at different velocities, leading to a zero-mass soliton at certain velocity.

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Article Title: Observation of Quantized Exciton Energies in Monolayer

Authors: Tianmeng Wang, Zhipeng Li, Zhengguang Lu, Yunmei Li, Shengnan Miao, Zhen Lian, Yuze Meng, Marl

Keywords: quantum exciton, monolayer

Abstract: Quantized energy levels are one of the hallmarks of quantum mechanics at the atomic level. The manifestation of quantization in macroscopic physical systems has showcased important quantum phenomena, such as quantized conductance in (fractional) quantum Hall effects and quantized vortices in superconductors. Here we report the first experimental observation of quantized exciton energies in a macroscopic system with strong Coulomb interaction, monolayer WSe₂ crystal under a strong magnetic field. Employing helicity-resolved magnetorefectance spectroscopy, we observe a striking ladder of plateaus as a function of the gate voltage for both exciton resonance in one valley and exciton-polariton branch in the opposite valley, thanks to the inter-Landau levels transitions governed by unique valley-selective selection rules. The observed quantized excitation energy level spacing sensitively depends on the doping level, indicating strong many-body effects.

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Publication Location:

Article Title: Quantum spiral spin-tensor magnetism

Authors: Xiaofan Zhou, Xi-Wang Luo, Gang Chen, Suotang Jia, Chuanwei Zhang

Keywords: spiral magnetism, spin-tensor

Abstract: The characterization of quantum magnetism in a large spin ($S=1$) system naturally involves both spin vectors and spin tensors. While certain types of spin-vector (e.g., ferromagnetic, spiral) and spin-tensor (e.g., nematic in frustrated lattices) orders have been investigated separately, the coexistence and correlation between them have not been well explored. Here, we propose a quantum spiral spin-tensor order on a spin-1 Heisenberg chain subject to a spiral spin-tensor Zeeman field, which can be experimentally realized using a Raman-dressed cold atom optical lattice. We develop a method to fully characterize quantum phases of such spiral tensor magnetism with the coexistence of spin-vector and spin-tensor orders as well as their correlations using eight geometric parameters. Our method provides a powerful tool for characterizing spin-1 quantum magnetism and opens an avenue for exploring magnetic orders and spin-tensor electronics and atomtronics in large-spin systems.

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Article Title: Topological phases in pseudospin-1 Fermi gases with two-dimensional spin-orbit coupling

Authors: Junpeng Hou, Haiping Hu, Chuanwei Zhang

Keywords: topological, spin-1, spin-orbit

Abstract: The recent experimental realization of spin-orbit (SO) coupling for ultracold bosons and fermions opens an exciting avenue for engineering quantum matter that may be challenging to realize in solid-state materials such as SO-coupled pseudospin-1 fermions. While one-dimensional SO coupling for spin-1 bosons has been experimentally realized, the generation of two-dimensional (2D) SO coupling and its topological properties are largely unexplored. Here we propose an experimental scheme for realizing a 2D Rashba-type SO coupling in a square lattice for pseudospin-1 Fermi gases. Because of the extended spin degree of freedom, many interesting topological phases could exist without relying on lattice point group symmetries that are crucial in solid-state materials. These exotic phases include triply degenerate points, quadratic band touching, a large Chern number ($C=5$) superfluid with five Majorana modes, triple-Weyl fermions, and so on.

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Article Title: In-Plane Zeeman-Field-Induced Majorana Corner and Hinge Modes in an

Authors: Ya-Jie Wu, Junpeng Hou, Yun-Mei Li, Xi-Wang Luo, Xiaoyan Shi, Chuanwei Zhang

Keywords: Majorana corner modes, s-wave superconductor heterostructure

Abstract: Second-order topological superconductors host Majorana corner and hinge modes in contrast to conventional edge and surface modes in two and three dimensions. However, the realization of such second-order corner modes usually demands unconventional superconducting pairing or complicated junctions or layered structures. Here we show that Majorana corner modes could be realized using a 2D quantum spin Hall insulator in proximity contact with an s-wave superconductor and subject to an in-plane Zeeman field. Beyond a critical value, the in-plane Zeeman field induces opposite effective Dirac masses between adjacent boundaries, leading to one Majorana mode at each corner. A similar paradigm also applies to 3D topological insulators with the emergence of Majorana hinge states. Avoiding complex superconductor pairing and material structure, our scheme provides an experimentally realistic platform for implementing Majorana corner and hinge states.

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Article Title: Active Perovskite Hyperbolic Metasurface

Authors: Zhitong Li, Joseph S. T. Smalley, Ross Haroldson, Dayang Lin, Roberta Hawkins, Abouzar Gharajeh, Ji

Keywords: Hyperbolic Metasurface

Abstract: A special class of anisotropic media, hyperbolic metamaterials and metasurfaces (HMMs), has attracted much attention in recent years due to its unique ability to manipulate and engineer electromagnetic waves on the subwavelength scale. Because all HMM designs require metal–dielectric composites, the unavoidable metal loss at optical frequencies inspired the development of active HMMs, wherein a gain material is incorporated to compensate for the metal loss. Here, we experimentally demonstrate a luminescent active HMM on silicon that operates at near 750 nm, in which the dielectric constituent is composed entirely of a solution-processed metal-halide perovskite gain. We show the extreme anisotropy of the HMM with microphotoluminescence measurements through the observation of high degrees of linear polarization that are greater than 0.8 in both the emission and absorption.

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Article Title: Phonon-exciton Interactions in WSe₂ under a quantizing magnetic field

Authors: Zhipeng Li, Tianmeng Wang, Shengnan Miao, Yunmei Li, Zhenguang Lu, Chenhao Jin, Zhen Lian, Yuze

Keywords: Phonon exciton interaction, quantizing magnetic field

Abstract: Strong many-body interaction in two-dimensional transitional metal dichalcogenides provides a unique platform to study the interplay between different quasiparticles, such as prominent phonon replica emission and modified valley-selection rules. A large out-of-plane magnetic field is expected to modify the exciton-phonon interactions by quantizing excitons into discrete Landau levels, which is largely unexplored. Here, we observe the Landau levels originating from phonon-exciton complexes and directly probe exciton-phonon interaction under a quantizing magnetic field. Phonon-exciton interaction lifts the inter-Landau-level transition selection rules for dark trions, manifested by a distinctively different Landau fan pattern compared to bright trions. This allows us to experimentally extract the effective mass of both holes and electrons. The onset of Landau quantization coincides with a significant increase of the valley-Zeeman shift, suggesting strong many-body effects on the phonon-e

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Article Title: Giant Valley-polarized Rydberg Excitons in Monolayer WSe₂ Revealed by Magneto-photocurrent Spectroscopy

Authors: Tianmeng Wang, Zhipeng Li, Yunmei Li, Zhengguang Lu, Shengnan Miao, Zhen Lian, Yuze Meng, Mar

Keywords: Rydberg excitons

Abstract: A strong Coulomb interaction could lead to a strongly bound exciton with high-order excited states, similar to the Rydberg atom. The interaction of giant Rydberg excitons can be engineered for a correlated ordered exciton array with a Rydberg blockade, which is promising for realizing quantum simulation. Monolayer transition metal dichalcogenides, with their greatly enhanced Coulomb interaction, are an ideal platform to host the Rydberg excitons in two dimensions. Here, we employ helicity-resolved magneto-photocurrent spectroscopy to identify Rydberg exciton states up to 11s in monolayer WSe₂. Notably, the radius of the Rydberg exciton at 11s can be as large as 214 nm, orders of magnitude larger than the 1s exciton. The giant valley-polarized Rydberg exciton not only provides an exciting platform to study the strong exciton–exciton interaction and nonlinear exciton response but also allows the investigation of the different interplay between the Coulomb interaction and Landau quantization.

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Article Title: Robust Weyl points in a one-dimensional superlattice with transverse spin-orbit coupling

Authors: Xi-Wang Luo, Chuanwei Zhang

Keywords: Weyl points, spin-orbit coupling

Abstract: Weyl points, synthetic magnetic monopoles in the three-dimensional momentum space, are the key features of topological Weyl semimetals. The observation of Weyl points in ultracold atomic gases usually relies on the realization of high-dimensional spin-orbit coupling (SOC) for two pseudospin states (i.e., spin 1/2), which requires complex laser configurations and precise control of laser parameters, thus, has not been realized in experiment. Here, we propose that robust Weyl points can be realized using one-dimensional triple-well superlattices (spin-1/three-band systems) with two-dimensional transverse SOC achieved by Raman-assisted tunnelings. The presence of the third band is responsible to the robustness of the Weyl points against system parameters (e.g., Raman laser polarization, phase, incident angle, etc.). Different from a spin-1/2 system, the nontrivial topology of Weyl points in such spin-1 system is characterized by both spin vector and tensor textures, which can be probed us

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Article Title: Tunable flux through a synthetic Hall tube of neutral fermions

Authors: Xi-Wang Luo, Jing Zhang, Chuanwei Zhang

Keywords: Synthetic Hall tube

Abstract: A Hall tube with a tunable flux is an important geometry for studying quantum Hall physics, but its experimental realization in real space is still challenging. Here we propose to realize a synthetic Hall tube with tunable flux in a one-dimensional optical lattice with the synthetic ring dimension defined by atomic hyperfine states. We investigate the effects of the flux on the system topology and study its quench dynamics. Utilizing the tunable flux, we show how to realize topological charge pumping, where interesting charge flow and transport are observed in rotated spin basis. Finally, we show that the recently observed quench dynamics in a synthetic Hall tube can be explained by the random flux existing in the experiment.

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Publication Location:

Article Title: Majorana corner pairs in a two-dimensional s -wave cold atomic superfluid

Authors: Ya-Jie Wu, Xi-Wang Luo, Junpeng Hou, Chuanwei Zhang

Keywords: Majorana corner pairs, s -wave superfluid

Abstract: We propose a method to prepare Majorana pairs at the corners of imprinted defects on a two-dimensional cold-atom optical lattice with s -wave superfluid pairing. Different from previous proposals that manipulate the effective Dirac masses, our scheme relies on the sign flip of the spin-orbit coupling at the corners, which can be tuned in experiments by adjusting the angle of incident Raman lasers. The Majorana corner pairs are found to be located at the interface between two regimes with opposite spin-orbit coupling strengths in an anticlockwise direction and are robust against certain symmetry-persevered perturbations. Our work provides a way for implementing and manipulating Majorana pairs with existing cold-atom techniques.

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Publication Location:

Article Title: Supersymmetry-assisted high-fidelity ground-state preparation of a single neutral atom in an optical tweezer

Authors: Xi-Wang Luo, Mark G. Raizen, Chuanwei Zhang

Keywords: supersymmetry, single atom, optical tweezer

Abstract: Arrays of neutral-atom qubits in optical tweezers are a promising platform for quantum computation. Despite experimental progress, a major roadblock for realizing neutral-atom quantum computation is the qubit initialization. Here we propose that supersymmetry, a theoretical framework developed in particle physics, can be used for ultrahigh-fidelity initialization of neutral-atom qubits. We show that a single atom can be deterministically prepared in the vibrational ground state of an optical tweezer by adiabatically extracting all excited atoms to a supersymmetric auxiliary tweezer. The scheme works for both bosonic and fermionic atom qubits trapped in realistic Gaussian optical tweezers and may pave the way for realizing large-scale quantum computation, simulation, and information processing with neutral atoms.

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Publication Location:

Article Title: Two-dimensional non-Hermitian topological phases induced by asymmetric hopping in a one-dimensional superlattice

Authors: Junpeng Hou, Ya-Jie Wu, Chuanwei Zhang

Keywords: Non-Hermitian, topological, superlattice

Abstract: Non-Hermitian systems can host topological states with unusual topological invariants and bulk-edge correspondences that are distinct from conventional Hermitian systems. Here we show that two unique classes of non-Hermitian two-dimensional topological phases, a $2\mathbb{Z}$ non-Hermitian Chern insulator and a $\mathbb{Z}2$ topological semimetal, can be realized by solely tuning staggered non-Hermitian or asymmetric hopping strengths in a one-dimensional (1D) superlattice. These non-Hermitian topological phases support real edge modes due to robust PT-symmetric-like spectra and can coexist in a certain parameter regime. The proposed phases can be experimentally realized in photonic or atomic systems and may open an avenue for exploring unique classes of non-Hermitian topological phases with 1D superlattices.

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Publication Location:

Article Title: Spin-twisted Optical Lattices: Tunable Flat Bands and Larkin-Ovchinnikov Superfluids

Authors: Xi-Wang Luo, Chuanwei Zhang

Keywords: Spin-twisted, flat band, superfluids

Abstract: Moiré superlattices in twisted bilayer graphene and transition-metal dichalcogenides have emerged as a powerful tool for engineering novel band structures and quantum phases of two-dimensional quantum materials. Here we investigate Moiré physics emerging from twisting two independent hexagonal optical lattices of atomic (pseudo-)spin states (instead of bilayers) that exhibit remarkably different physics from twisted bilayer graphene. We employ a momentum-space tight-binding calculation that includes all range real-space tunnelings and show that all twist angles $\sim 6^\circ$ can become magic and support gapped flat bands. Because of the greatly enhanced density of states near the flat bands, the system can be driven to superfluidity by weak attractive interaction. Strikingly, the superfluid phase corresponds to a Larkin-Ovchinnikov state with finite momentum pairing that results from the interplay between flat bands and interspin interactions in the unique single-layer spin-twisted lattice

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Article Title: Topological phase transitions driven by non-Hermiticity in quantum spin Hall insulators

Authors: Junpeng Hou, Ya-Jie Wu, Chuanwei Zhang

Keywords: non-Hermitian, topological, quantum spin Hall

Abstract: The interplay between non-Hermiticity and topology opens an exciting avenue for engineering novel topological matter with unprecedented properties. While previous studies have mainly focused on one-dimensional systems or Chern insulators, here we investigate topological phase transitions to and from quantum spin Hall (QSH) insulators driven by non-Hermiticity. We show that a trivial to QSH insulator phase transition can be induced by solely varying non-Hermitian terms, and there exists exceptional edge arcs in QSH phases. We establish two topological invariants for characterizing the non-Hermitian phase transitions: (i) with time-reversal symmetry, the biorthogonal Z_2 invariant based on non-Hermitian Wilson loops, and (ii) without time-reversal symmetry, a biorthogonal spin Chern number through biorthogonal decompositions of the Bloch bundle of the occupied bands. These topological invariants can be applied to a wide class of non-Hermitian topological phases beyond Chern classes, and

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Publication Location:

Article Title: Pseudo-Goldstone excitations in a striped Bose-Einstein condensate

Authors: Guan-Qiang Li, Xi-Wang Luo, Junpeng Hou, Chuanwei Zhang

Keywords: Pseudo-Goldstone modes, BEC

Abstract: Significant experimental progress has been made recently for observing long-sought supersolidlike states in Bose-Einstein condensates, where spatial translational symmetry is spontaneously broken by anisotropic interactions to form a stripe order. Meanwhile, the superfluid stripe ground state was also observed by applying a weak optical lattice that forces the symmetry breaking. Despite the similarity of the ground states, here we show that these two symmetry breaking mechanisms can be distinguished by their collective excitation spectra. In contrast to gapless Goldstone modes of the spontaneous stripe state, we propose that the excitation spectra of the forced stripe phase can provide direct experimental evidence for the gapped pseudo-Goldstone modes. We characterize the pseudo-Goldstone mode of such lattice-induced stripe phase through its excitation spectrum and static structure factor. Our work may pave the way for exploring spontaneous and forced or approximate symmetry breaking in

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Article Title: Nonlinear Dynamics in a Synthetic Momentum-State Lattice

Authors: Fangzhao Alex An, Bhuvanesh Sundar, Junpeng Hou, Xi-Wang Luo, Eric J. Meier, Chuanwei Zhang, Kz

Keywords: synthetic momentum lattice, BEC

Abstract: The scope of analog simulation in atomic, molecular, and optical systems has expanded greatly over the past decades. Recently, the idea of synthetic dimensions—in which transport occurs in a space spanned by internal or motional states coupled by field-driven transitions—has played a key role in this expansion. While approaches based on synthetic dimensions have led to rapid advances in single-particle Hamiltonian engineering, strong interaction effects have been conspicuously absent from most synthetic dimensions platforms. Here, in a lattice of coupled atomic momentum states, we show that atomic interactions result in large and qualitative changes to dynamics in the synthetic dimension. We explore how the interplay of nonlinear interactions and coherent tunneling enriches the dynamics of a one-band tight-binding model giving rise to macroscopic self-trapping and phase-driven Josephson dynamics with a nonsinusoidal current-phase relationship, which can be viewed as stemming from a non

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Date Submitted: 8/21/22 12:00AM **Date Published:** 4/1/22 5:00AM
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Article Title: Quantum Squeezing and Sensing with Pseudo-Anti-Parity-Time Symmetry

Authors: Xi-Wang Luo, Chuanwei Zhang, Shengwang Du

Keywords: Quantum, squeezing, sensing, PT-symmetry

Abstract: The emergence of parity-time (PT) symmetry has greatly enriched our study of symmetry-enabled non-Hermitian physics, but the realization of quantum PT symmetry faces an intrinsic issue of unavoidable symmetry-breaking Langevin noises. Here we construct a quantum pseudo-anti-PT (pseudo-APT) symmetry in a two-mode bosonic system without involving Langevin noises. We show that the spontaneous pseudo-APT symmetry breaking leads to an exceptional point, across which there is a transition between different types of quantum squeezing dynamics; i.e., the squeezing factor increases exponentially (oscillates periodically) with time in the pseudo-APT-symmetric (broken) region. Such dramatic changes of squeezing factors and quantum dynamics near the exceptional point are utilized for ultraprecision quantum sensing. These exotic quantum phenomena and sensing applications can be experimentally observed in two physical systems: spontaneous wave mixing nonlinear optics and atomic Bose-Einstein

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Publication Location:

Article Title: Wavelength conversion for single-photon polarization qubits through continuous-variable quantum teleportation

Authors: Xi-Wang Luo, Chuanwei Zhang, Irina Novikova, Chen Qian, Shengwang Du

Keywords: wavelength conversion, photonic qubit, cold atoms

Abstract: A quantum internet connects remote quantum processors that need to interact and exchange quantum signals over a long distance through photonic channels. However, these quantum nodes operate at the wavelength ranges unsuitable for long-distance transmission. Therefore, quantum wavelength conversion to telecom bands is crucial for long-distance quantum networks based on optical fiber. Here, we propose wavelength conversion devices for single-photon polarization qubits using continuous-variable quantum teleportation that can efficiently convert qubits between near-infrared (780–795 nm suitable for interacting with atomic quantum nodes) and telecom wavelength (1300–1500 nm suitable for long-distance transmission). The teleportation uses entangled photon fields (i.e., nondegenerate two-mode squeezed state) that can be generated by four-wave mixing in a rubidium atomic gas using a diamond configuration of atomic transitions. The entangled fields can be emitted in two orthogonal polarizations

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Volume: Issue:

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Publication Location:

Article Title: Excitonic insulator in a heterojunction moiré superlattice

Authors: Dongxue Chen, Zhen Lian, Xiong Huang, Ying Su, Mina Rashetnia, Lei Ma, Li Yan, Mark Blei, Li Xiang,

Keywords: exciton insulator, Moire lattice, topology

Abstract: We demonstrate a generic mechanism to realize topological flat minibands by confining massive Dirac fermions in a periodic moiré potential, which can be achieved in a heterobilayer of transition metal dichalcogenides. We show that the topological phase can be protected by the symmetry of moiré potential and survive to arbitrarily large Dirac band gap. We take the MoTe₂/WSe₂ heterobilayer as an example and find that the topological phase can be driven by a vertical electric field. By projecting the Coulomb interaction onto the topological fat minibands, we identify a correlated Chern insulator at half filling and a quantum valley-spin Hall insulator at full filling which explains the topological states observed in the MoTe₂/WSe₂ in the experiment. Our work clarifies the importance of Dirac structure for the topological minibands and unveils a general strategy to design topological moiré materials.

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Publication Location:

Article Title: Massive Dirac fermions in moiré superlattices: A route towards topological flat minibands and correlated topological insulators

Authors: Ying Su, Heqiu Li, Chuanwei Zhang, Kai Sun, Shi-Zeng Lin

Keywords: massive Dirac fermions, Morie lattice, topology

Abstract: We demonstrate a generic mechanism to realize topological flat minibands by confining massive Dirac fermions in a periodic moiré potential, which can be achieved in a heterobilayer of transition metal dichalcogenides. We show that the topological phase can be protected by the symmetry of moiré potential and survive to arbitrarily large Dirac band gap. We take the MoTe₂/WSe₂ heterobilayer as an example and find that the topological phase can be driven by a vertical electric field. By projecting the Coulomb interaction onto the topological fat minibands, we identify a correlated Chern insulator at half filling and a quantum valley-spin Hall insulator at full filling which explains the topological states observed in the MoTe₂/WSe₂ in the experiment. Our work clarifies the importance of Dirac structure for the topological minibands and unveils a general strategy to design topological moiré materials.

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Article Title: Tuning moiré excitons and correlated electronic states through layer degree of freedom

Authors: Dongxue Chen, Zhen Lian, Xiong Huang, Ying Su, Mina Rashetnia, Li Yan, Mark Blei, Takashi Taniguchi

Keywords: Moiré superlattice, multiple layers, excitons

Abstract: Moiré coupling in transition metal dichalcogenides (TMDCs) superlattices introduces flat minibands that enable strong electronic correlation and fascinating correlated states, and it also modifies the strong Coulomb-interaction-driven excitons and gives rise to moiré excitons. Here, we introduce the layer degree of freedom to the WSe₂/WS₂ moiré superlattice by changing WSe₂ from monolayer to bilayer and trilayer. We observe systematic changes of optical spectra of the moiré excitons, which directly confirm the highly interfacial nature of moiré coupling at the WSe₂/WS₂ interface. In addition, the energy resonances of moiré excitons are strongly modified, with their separation significantly increased in multilayer WSe₂/monolayer WS₂ moiré superlattice. The additional WSe₂ layers also modulate the strong electronic correlation strength, evidenced by the reduced Mott transition temperature with added WSe₂ layer(s). The layer dependence of both moiré excitons and correlated electronic states

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Signature: Chuanwei Zhang

Signature Date: 1/23/23 11:45AM

ARO Final Report

Award Title: Quantum phases and dynamics in periodically driven ultra-cold atomic gases

Award Number: W911NF-17-1-0128

Program Manager: Margaret Shea

Principle Investigator: Chuanwei Zhang

March 15, 2017 – November 14, 2022

1. Major research activities

Ultra-cold atomic gases provide a clean and highly controllable platform for emulating many-body phenomena and engineering new quantum materials. In cold atomic gases, external potentials can be induced periodically not only in the real space (i.e., optical lattices), but also in the time domain. Such periodic modulation of the system Hamiltonian, together with some recently developed experimental tools such as spin-orbit coupling, open a broad avenue for discovering new quantum matter. In this project, we utilize various experimental tools with the periodic driving of system parameters for engineering new many-body quantum matters and exploring their non-equilibrium dynamics in cold atomic gases. Our proposed research contains both fast time modulation for Floquet quantum matter and adiabatic modulation for topological transport of cold atoms. We also explore novel quantum phases and dynamics in time-dependence potentials. Our theoretical efforts will be closely coupled to ongoing experimental efforts at Washington State University, Purdue University, UIUC, and University of Washington.

Some highlights in the past five years include:

- 1) Parity-Time (PT) symmetry has been widely studied in classical wave systems, but the realization of quantum PT-symmetry faces unavoidable symmetry-breaking Langevin noises. We construct a quantum pseudo-anti-PT symmetry in a two-mode bosonic system without involving Langevin noises. The pseudo-APT phase transition across the exceptional point yields a dramatic transition between different types of quantum squeezing behaviors, which are utilized for ultra-precision quantum sensing with divergent sensitivity. (X.-W. Luo, C. Zhang, S. Du, Phys. Rev. Lett. 128, 173602 (2022))
- 2) While quantum simulations based on synthetic dimensions have led to rapid advances in single-particle Hamiltonian engineering, strong interaction effects have been conspicuously absent from most synthetic dimensions platforms. In a lattice of coupled atomic momentum states, we showed that atomic interactions result in large and qualitative changes to dynamics in the synthetic dimension. (F. A. An, B. Sundar, J. Hou, X.-W. Luo, E. J. Meier, C. Zhang, K. R. A. Hazzard, B. Gadway, Phys. Rev. Lett. 127.130401 (2021) Editors' Suggestions)
- 3) Contrary to a driven classical system that exhibits chaos phenomena and diffusive energy growth, a driven quantum system can exhibit dynamical localization that features energy saturation. However, the evolution of the dynamically localized state in the presence of many-body interactions has for long remained an open question. Here we realized a many-body quantum kicked rotor with a 1D ultracold gas periodically kicked by a pulsed optical lattice, and observed the interaction-driven emergence of dynamical delocalization. This observed onset of many-body quantum chaos and its characterization by the accompanying theoretical modeling introduce new tools to study many-body localization-delocalization phenomena in the synthetic momentum space. (J. H. See Toh, K. C. McCormick, X. Tang, Y. Su, X.-W. Luo, C. Zhang, and S. Gupta, Nature Physics, 18, 1297 (2022))

- 4) We investigated Moire physics emerging from twisting two independent hexagonal optical lattices of atomic (pseudo-)spin states (instead of bilayers), which exhibits remarkably different physics from twisted bilayer graphene. Our work should open a new playfield for studying many-body quantum phases and twistronics with new types of twisted pseudospin degree of freedom. (X.-W. Luo, C. Zhang, Phys. Rev. Lett. 126, 103201 (2021))
- 5) Second-order topological superconductors host Majorana corner and hinge modes in contrast to conventional edge and surface modes. The realization of such second-order corner modes usually demands unconventional superconducting pairing or complicated junctions/layered structures. We showed that Majorana corner modes could be realized on an experimentally available heterostructure composing of a 2D quantum spin Hall insulator and an s-wave superconductor by simply applying an in-plane Zeeman field. Avoiding complex superconductor pairing and material structure, our scheme provides an experimentally realistic platform for implementing Majorana corner and hinge states. The same experimental ingredient could also be realized in ultracold atomic gases. (Y.-J. Wu, J. Hou, Y.-M. Li, X.-W. Luo, C. Zhang, Phys. Rev. Lett. 124, 227001 (2020)).
- 6) Collaborating with Peter Engels' experimental group at Washington State University, we theoretically conceived a non-magnetic one-way spin switch device and experimentally demonstrated its design principle utilizing a Bose-Einstein condensate (BEC) as an atomtronic device. The paper was also selected as monthly Editors' Highlights for Nature Communications (M. E. Mossman, J. Hou, X.-W. Luo, C. Zhang, P. Engels, Nat. Commun. 10, 3381 (2019)).
- 7) We showed that higher-order topological corner states can emerge by introducing staggered on-site gain/loss to a Hermitian system in a trivial phase. For such a non-Hermitian system, we established a general bulk-corner correspondence, which can be applied to a wide class of non-Hermitian systems with higher-order topological orders. Such gain/loss induced higher-order topological corner states can be experimentally realized using photons in coupled cavities or cold atoms in optical lattices. (X.-W. Luo, C. Zhang, Phys. Rev. Lett. 123, 073601 (2019)).
- 8) We proposed a new type of Floquet physics for a Bose-Einstein condensate (BEC) subject to a shaken lattice generated inside a cavity, where the shaken lattice and atomic Floquet bands are mutually dependent, resulting in self-adapted Floquet dynamics. In particular, the shaken lattice induces Floquet quasienergy bands for the BEC, whose backaction leads to a self-adapted dynamical normal superradiant phase transition for the shaken lattice (X.-W. Luo, C. Zhang, Phys. Rev. Lett. 120, 263202 (2018)).
- 9) As an analogy to super-solids, we proposed a new quantum state named superfluid quasicrystal that possesses both superfluid and quasi-crystalline orders and showed that it can be realized with a simple experimental setup. The study will advance our understanding of both quasicrystals and superfluids and open a significant new area of research: super-quasicrystals (J. Hou, H. Hu, K. Sun, C. Zhang, Phys. Rev. Lett. 120, 060407 (2018)).
- 10) We proposed to realize the Josephson effects in the momentum space by coupling two band minima of a spin-orbit coupled BEC. Collaborated with Peter Engels' experimental group, we showed that such momentum space hopping between two band minima using a weak optical lattice enables the experimental realization of a superfluid stripe phase in a spin-orbit coupled BEC (J. Hou, X.-W. Luo, K. Sun, T. Bersano, V. Gokhroo, S. Mossman, P. Engels, C. Zhang, Phys. Rev. Lett. 120, 120401 (2018). PRL Editors' Suggestions; T. M. Bersano, J.

Hou, S. Mossman, V. Gokhroo, X.-W. Luo, K. Sun, C. Zhang, P. Engels, Phys. Rev. A 99, 051602(R) (2019)).

These research activities lead to 49 papers published in peer-reviewed journals, including 2 in Nature Physics, 4 in Nature Communications, 1 in Physical Review X and 13 in Physical Review Letters. Three papers have been selected as Editors' suggestions by editors of Physical Review Letters and Physical Review Research. Our work on superfluid quasicrystals has been widely reported by various news media, including Newsweek magazine.

In October 2017, the PI was elected to the Fellow of American Physical Society, with the citation: "*For seminal contributions to theoretical research in ultracold atomic physics, including studies of spin-orbit coupled quantum gases, topological superfluids with Majorana or Weyl fermions, and Fulde-Ferrell superfluid states.*" The cited works have been supported by ARO in the past.

In addition to these research activities, the ARO grant has supported the PI on various education activities, such as the mentoring of graduate and undergraduate students in the University of Texas at Dallas. Two graduate students (Matthew Maisberger, Junpeng Hou) who worked on the ARO-grant related research have received PhD during the grant period.

2. Results

Because of the theoretical nature of our research, our research findings covered many different topics although they shared similar goal of the project. Our research also involves close collaboration with experimental groups with joint experiment-theory publications. In the following we describe several major research findings in the past five years resulted from the PI's research activities.

2.1. Spin-tensor--momentum-coupled Bose-Einstein condensates,

Xi-Wang Luo, Kuei Sun, Chuanwei Zhang,
Phys. Rev. Lett. 119, 193001 (2017)

The recent experimental realization of spin-orbit coupling for ultracold atomic gases provides a powerful platform for exploring many interesting quantum phenomena. In these studies, spin represents spin vector (spin-1/2 or spin-1) and orbit represents linear momentum. Here we propose a scheme to realize a new type of spin-tensor--momentum coupling (STMC) in spin-1 ultracold atomic gases. We study the ground state properties of interacting Bose-Einstein condensates (BECs) with STMC and find interesting new types of stripe superfluid phases and multicritical points for phase transitions. Furthermore, we show that a stripe phase with a long tunable period and high visibility of density modulation can be dynamically generated using STMC, paving the way for direct experimental observation of the long-sought stripe phases. Our scheme for generating STMC can be generalized to other systems and may open the door for exploring novel quantum physics and device applications.

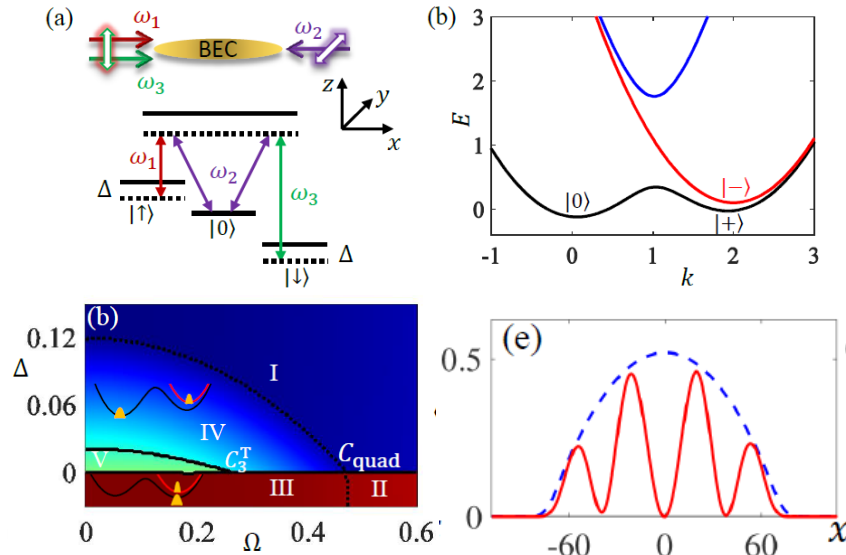


Figure 1: (Top) Proposed experimental setup and resulting band structure. (Bottom) Ground state phase diagram and the dynamical stripe phases.

2.2. Topological Triply-Degenerate Points Induced by Spin-Tensor-Momentum Couplings

Haiping Hu, Junpeng Hou, Fan Zhang, Chuanwei Zhang,
Phys. Rev. Lett. 120, 240401 (2018).

The recent discovery of triply-degenerate points (TDPs) in topological materials has opened a new perspective toward the realization of novel quasiparticles without counterparts in quantum field theory. The emergence of such protected nodes is often attributed to spin-vector-momentum coupling (SVMC). Here we show that the interplay between spin-tensor-momentum coupling (STMC) and SVMC can induce three types of TDPs, classified by their different Chern numbers ($C = \pm 2, \pm 1, 0$). Under a Zeeman field, type-I ($C = \pm 2$) and type-II ($C = \pm 1$) TDPs can be lifted into two Weyl points carrying the same and opposite monopole charges, respectively, whereas a type-III ($C = 0$) TDP is broken into two pairs of Weyl points of opposite charges. We find that different TDPs of the same type are connected by intriguing Fermi arcs on surfaces, and that transitions between different types are accompanied by level crossings along high-symmetry lines. We further propose an experimental scheme for realizing such TDPs in cold-atom optical lattices. Our results provide a framework for studying STMC-induced TDPs and other exotic quasiparticles.

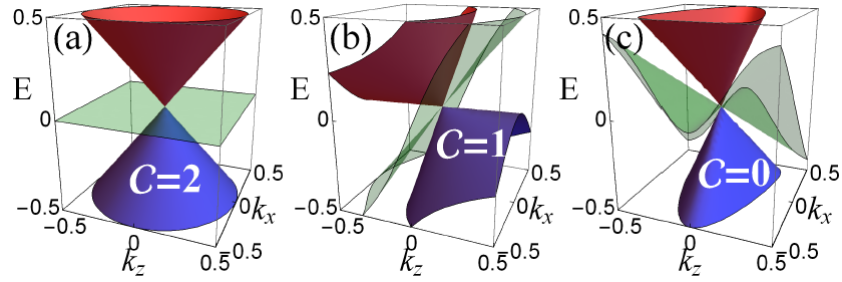


Figure 2: Three types of triply-degenerate points with different Chern numbers induced by spin-tensor momentum couplings.

2.3: Superfluid-Quasicrystal in a Bose-Einstein Condensate

Junpeng Hou, Haiping Hu, Kuei Sun, and Chuanwei Zhang

Phys. Rev. Lett. 117, 235304 (2016)

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A quasicrystal is a class of ordered structures defying conventional classification of solid crystals and may carry classically forbidden (e.g., fivefold) rotational symmetries. In view of long-sought supersolids, a natural question is whether a superfluid can spontaneously form quasicrystalline order that is not possessed by the underlying Hamiltonian, forming “superfluid-quasicrystals.” Here we show that a superfluidquasicrystal stripe state with the minimal fivefold rotational symmetry can be realized as the ground state of a Bose-Einstein condensate within a practical experimental scheme. There exists a rich phase diagram consisting of various superfluid-quasicrystal, supersolid, and plane-wave phases. Our scheme can be generalized for generating other higher-order (e.g., sevenfold) quasicrystal states, and provides a platform for investigating such new exotic quantum matter.

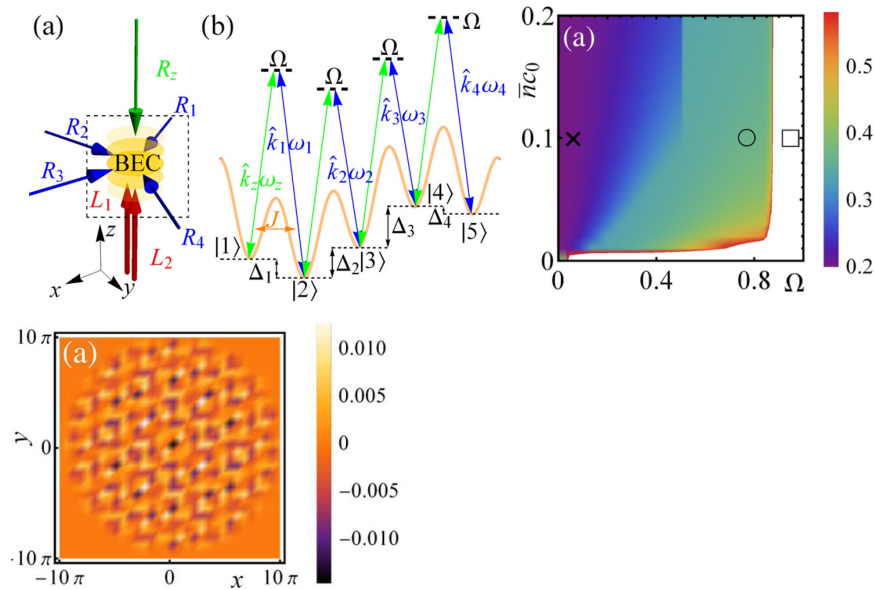


Figure 3: (Top Left) Proposed experimental scheme for generating superfluid quasicrystals. (Top right) phase diagram. (c) Real space density distribution for a superfluid quasicrystal in a harmonic trap.

2.4: Momentum Space Josephson Effects

Junpeng Hou, Xi-Wang Luo, Kuei Sun, Thomas Bersano, Vandna Gokhroo, Sean Mossman, Peter Engels, Chuanwei Zhang,

Phys. Rev. Lett. **120**, 120401 (2018). [PRL Editors' Suggestions](#)

The Josephson effect is a prominent phenomenon of quantum supercurrents that has been widely studied in superconductors and superfluids. Typical Josephson junctions consist of two real-space superconductors (superfluids) coupled through a weak tunneling barrier. Here we propose a momentum-space Josephson junction in a spin-orbit coupled Bose-Einstein condensate, where states with two different momenta are coupled through Raman-assisted tunneling. We show that Josephson currents can be induced not only by applying the equivalent of “voltages,” but also by tuning tunneling phases. Such tunneling-phase-driven Josephson junctions in momentum space are characterized through both full mean field analysis and a concise two-level model, demonstrating the important role of interactions between atoms. Our scheme provides a platform for experimentally realizing momentum-space Josephson junctions and exploring their applications in quantum-mechanical circuits.

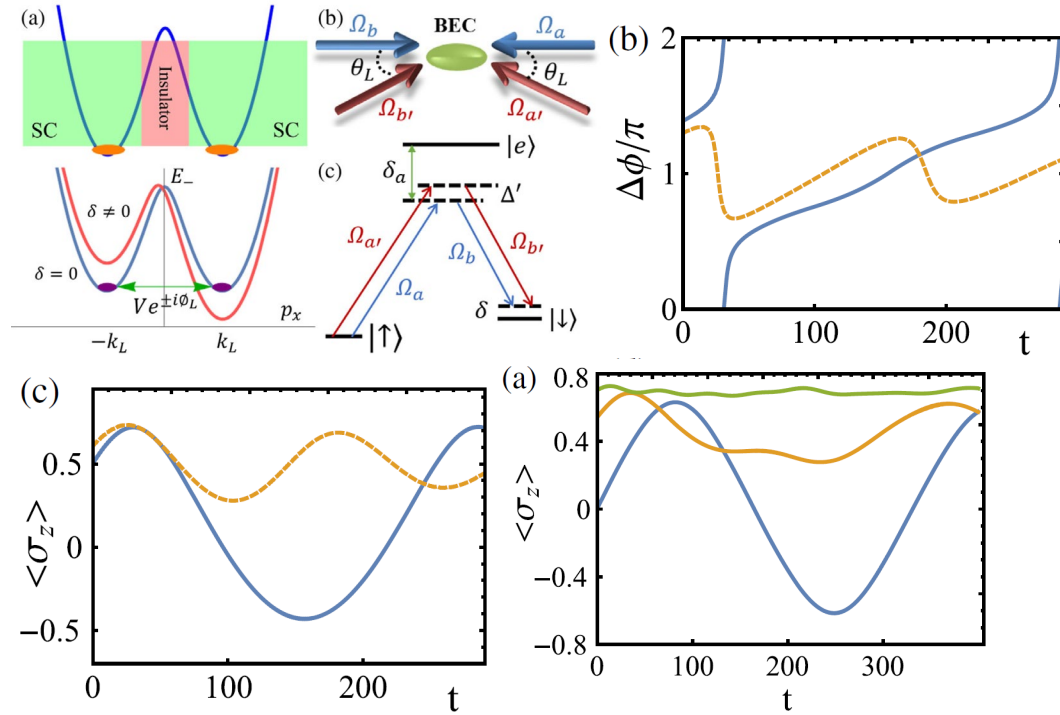


Figure 4: (Top Left) Proposed experimental scheme for realizing momentum space Josephson effect in a spin-orbit coupled ultra-cold atomic gas. (Top right) The phase oscillation for Josephson effect. (Bottom left) The spin polarization oscillation for weak interaction. (Bottom right) The spin polarization oscillation for strong interaction.

2.5: Self-Adapted Floquet Dynamics of Ultracold Bosons in a Cavity,

Xi-Wang Luo, Chuanwei Zhang,
Phys. Rev. Lett. **120**, 263202 (2018)

Floquet dynamics of a quantum system subject to periodic modulations of system parameters provides a powerful tool for engineering new quantum matter with exotic properties. While system dynamics is significantly altered, the periodic modulation itself is usually induced externally and independent of Floquet dynamics. Here we propose a new type of Floquet physics for a Bose-Einstein condensate (BEC) subject to a shaken lattice generated inside a cavity, where the shaken lattice and atomic Floquet bands are mutually dependent, resulting in self-adapted Floquet dynamics. In particular, the shaken lattice induces Floquet quasienergy bands for the BEC, whose backaction leads to a self-adapted dynamical normal superradiant phase transition for the shaken lattice. Such self-adapted Floquet dynamics shows two surprising and unique features: (i) The normal-superradiant phase transition possesses a hysteresis even without atom interactions. (ii) The dynamical atom-cavity steady state could exist at free energy maxima. The atom interactions strongly affect the phase transition of the BEC from zero to finite momenta. Our results provide a powerful platform for exploring self-adapted Floquet physics, which may open an avenue for engineering novel quantum materials.

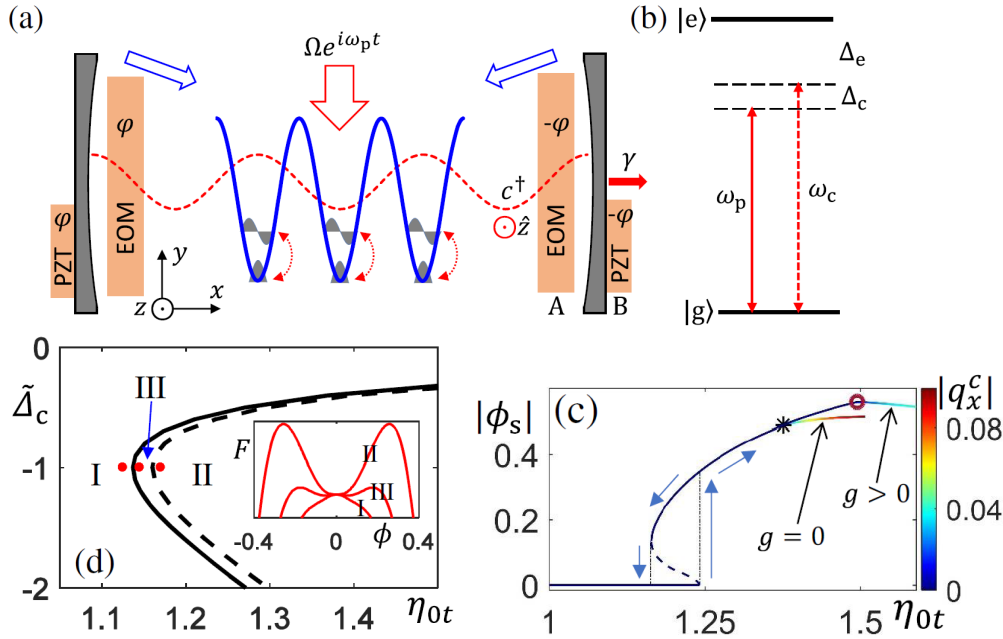


Figure 5: (Top) Experimental setup. (Bottom) Phase diagram and hysteresis phenomenon.

2.6. Majorana Doublets, Flat Bands, and Dirac Nodes in s-Wave Superfluids,

Haiping Hu, Fan Zhang, Chuanwei Zhang,
Phys. Rev. Lett. 121, 185302 (2018).

Topological superfluids are quantum states of matter hosting exotic quasiparticles such as Majorana fermions, which possess non-Abelian braiding statistics and are key ingredients for fault-tolerant topological quantum computing. In the presence of time-reversal symmetry, two Majorana fermions would be paired together, forming a Majorana Kramers pair (MKP). MKPs not only enjoy symmetry-protected non-Abelian braiding statistics, which constitutes advantages for quantum computing, but also bring various novel phenomena in condensed matter physics. However, the realization of time-reversal invariant topological superfluids and superconductors has long been hindered by the requirement of unconventional pairing, which is difficult to achieve in realistic systems. As a result, a stable platform of conventional pairing hosting MKPs is being greatly pursued, although not successful so far.

In this paper, we proposed to realize such a symmetry protected topological superfluid by utilizing conventional s-wave pairing and emergent symmetries in spin-orbit coupled ultracold Fermi gases, which are readily realized in current ultracold atomic experiments. Not only does this system support novel superfluid phases, including the time-reversal invariant topological superfluids and Dirac-nodal superfluids with associated MKPs, but also these phases are stable against pairing fluctuations that otherwise annihilate paired Majorana fermions in the widely studied time-reversal breaking (class D) topological superfluids. Our scheme provides a simple and unique platform for exploring MKPs and their applications in quantum computation. Our results may motivate further theoretical and experimental investigations on time-reversal invariant topological superfluids and their MKPs in both solid state and ultracold atomic systems.

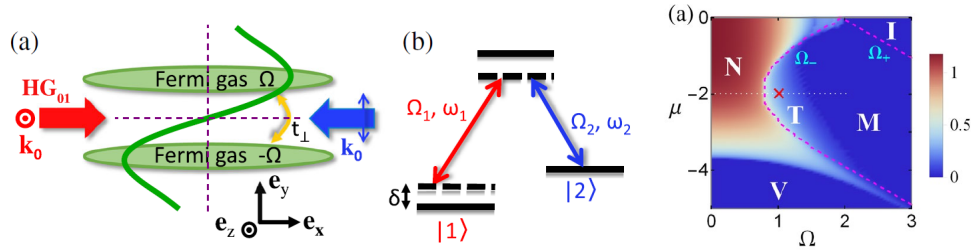


Figure 6: (Left) Proposed experimental setup for realizing time-reversal invariant two chain system. (Middle) Raman laser configuration. (Right) The phase diagram for the topological superfluids with MKPs.

2.7. Experimental realization of a non-magnetic one-way spin switch,
M. E. Mossman, Junpeng Hou, Xi-Wang Luo, Chuanwei Zhang*, P. Engels*,
Nature Communications **10**, 3381 (2019).

Controlling magnetism through non-magnetic means is crucial for future electronic devices such as magnetic data storage devices or integrated circuits as it provides ultra-low power and coherent control (Nat. Nanotechnol. 10 (2015)). In recent years, great experimental progress has been made in the field of electrical manipulation of magnetism in numerous material systems such as multiferroics (e.g., Nature 442, 759 (2006)), magnetic semiconductors (e.g., Science 332, 1065 (2011)), and 2D van der Waals magnets (e.g., Nature Materials 17, 406 (2018)). Such non-magnetic control requires strong coupling between magnetic and electric properties of underlying materials and leads to multi-functional capabilities of spintronic devices. However, these devices generally do not possess unidirectional functionality, where magnetism switch and electric controlling signal directions could be mutually coupled.

In this paper, we added this significant unidirectional functionality into a spintronic device by theoretically conceiving a non-magnetic one-way spin switch device and experimentally demonstrating its design principle utilizing a Bose-Einstein condensate (BEC) as an atomtronic device. Here the unidirectionality of the device stems from the breakdown of the famous Galilean invariance in the presence of spin-orbit coupling, a crucial ingredient for spintronic devices and topological materials that has recently been experimentally realized in ultracold atomic gases. Although both spin-orbit coupling and the breakdown of Galilean invariance are well known in solid state/cold atomic matter, utilizing them as a design principle for unidirectional spintronic/atomtronic devices was first proposed and realized in this paper.

Our proposed concept of a unidirectional spin switch device and its experimental demonstration may open an avenue for designing a new class of innovative quantum devices with unique functionalities. While we have demonstrated the device using a quantum degenerate gas, the design principle can also be applied to solid state materials and may stimulate further theoretical and experimental investigations of other one-way atomtronic and spintronic devices.

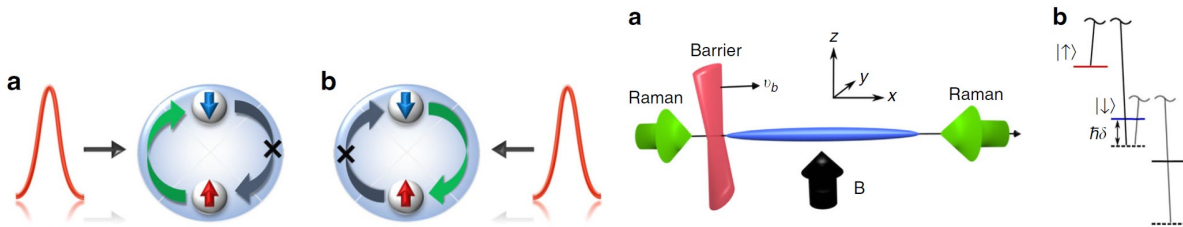


Figure 7: (Left panel): General concept and mechanism of a one-way spin switch. A control signal incoming from **a the left or **b** the right is able to switch the spin orientation of the system from $\uparrow$ to $\downarrow$ (**a**) or $\downarrow$ to $\uparrow$ (**b**) while the reverse processes are forbidden. (Right Panel) Experimental setup. **a** Two counter-propagating Raman beams applied along x induce SO coupling along the elongated axis of the BEC. A repulsive, spin-independent optical barrier is initially positioned outside of the BEC and then swept along the x-axis at a constant velocity, v_b . **b** Two pseudospin states, $|m_F = -1\rangle$ ($\equiv |\uparrow\rangle$) and 0 ($\equiv |\downarrow\rangle$), are Raman coupled with coupling strength Ω and detuning δ , while the $|m_F = +1\rangle$ state is effectively decoupled from the system.**

2.8: Higher-order topological corner states induced by gain and loss,

Xi-Wang Luo, Chuanwei Zhang
Phys. Rev. Lett. **123**, 073601 (2019).

The concept of topological phases has been generalized to higher-order topological insulators and superconductors with novel boundary states on corners or hinges, and such interesting topological states have been realized in photonic and electrical circuit systems. Meanwhile, recent experimental advances in controlling dissipation (such as gain and loss) open new possibilities in studying non-Hermitian topological phases, which exhibit a rich variety of unique properties without Hermitian counterparts (e.g., the non-Hermitian skin effects, bulk fermi arcs, exceptional rings, unconventional bulk-boundary correspondence). Therefore, two natural questions arise: 1) Can higher-order topological states be induced by simply controlling the on-site gain or loss? 2) Is there a generalized bulk-corner correspondence for the non-Hermitian higher-order topological states?

In this paper, we addressed these two important questions by considering a 2-dimensional lattice model and showed that higher-order topological corner states can emerge by simply introducing staggered on-site gain/loss to a Hermitian system in trivial phases. For such a non-Hermitian system, we established a general bulk-corner correspondence by developing a biorthogonal nested-Wilson-loop and edge-polarization theory, which can be applied to a wide class of non-Hermitian systems with higher-order topological orders. The theory gives rise to topological invariants characterizing the non-Hermitian topological multipole moments (i.e., corner states) that are protected by reflection or chiral symmetry. Such gain/loss induced higher-order topological corner states can be experimentally realized using photons in coupled cavities or cold atoms in optical lattices. Moreover, it is straightforward to generalize our non-Hermitian model and bulk-corner correspondence to higher-dimensional systems (e.g., 3-dimensional third-order topological phases with quantized octupole moment).

Our work offers a tunable method for manipulating higher-order topological corner states through dissipation control and paves the way for the study of various non-Hermiticity induced higher-order topological states of matter and the classifications of them.

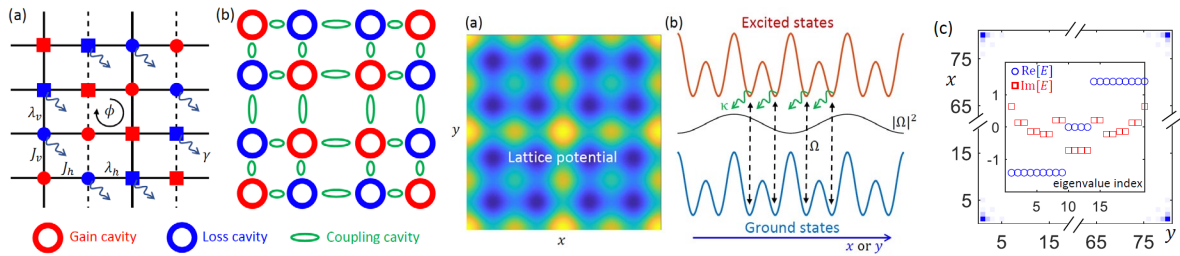


Figure 8: (Left panel) (a) Lattice representation of the non-Hermitian model. All sites in blue (red) have particle loss (gain) with a rate γ . (b) Experimental implementation of the lattice model in (a) using coupled arrays of micro-ring cavities. (Middle panel) Proposed experimental realization using cold atoms in optical lattices. (Right panel) Topological corner states in a 2D lattice.

2.9: Spin Current Generation and Relaxation in a Quenched Spin-Orbit Coupled Bose-Einstein Condensate

Chuan-Hsun Li, Chunlei Qu, Robert J. Niffenegger, Su-Ju Wang, Mingyuan He, David B. Blasing, Abraham Olson, Chris H. Greene, Yuli Lyanda-Geller, Qi Zhou, Chuanwei Zhang, Yong P. Chen,

Nature Communications **10**, 375 (2019).

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Understanding the effects of spin-orbit coupling (SOC) and many-body interactions on spin transport is important in condensed matter physics and spintronics. This topic has been intensively studied for spin carriers such as electrons but barely explored for charge-neutral bosonic quasiparticles (including their condensates), which hold promises for coherent spin transport over macroscopic distances. Here, we explored the effects of synthetic SOC (induced by optical Raman coupling) and atomic interactions on the spin transport in an atomic Bose-Einstein condensate (BEC), where the spin-dipole mode (SDM, actuated by quenching the Raman coupling) of two interacting spin components constitutes an alternating spin current. We experimentally observed that SOC significantly enhances the SDM damping while reducing the thermalization (the reduction of the condensate fraction). We also observed generation of BEC collective excitations such as shape oscillations. Our theory reveals that the SOC-modified interference, immiscibility, and interaction between the spin components can play crucial roles in spin transport.

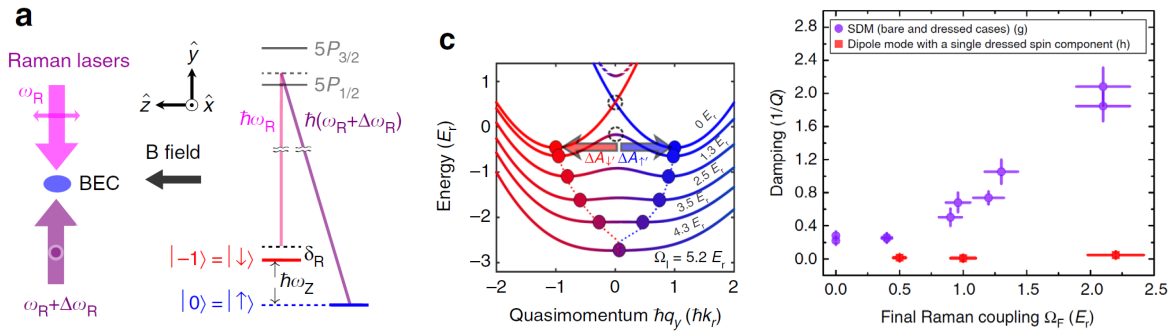


Figure 9: (Left) Experimental setup for generating spin-orbit coupling for Rb87 atoms. (Middle) Generation of spin-dependent gauge electric field through quenching Raman coupling strength. (c) Observed spin damping due to spin collision.

2.10. In-plane Zeeman field induced Majorana corner and hinge modes in an s-wave superconductor heterostructure,

Ya-Jie Wu, Junpeng Hou, Yun-Mei Li, Xi-Wang Luo, Chuanwei Zhang,
Phys. Rev. Lett. 124, 227001 (2020)

Higher-order topological superconductors are a new class of topological matters that have attracted great attention recently in the physics community. In conventional (i.e., first-order) topological superconductors, Majorana edge excitations appear at 1D edges of a 2D plane or 0D ends of a 1D line. In contrast, in a second-order topological superconductor, 0D Majorana corner modes can emerge at corners of a 2D plane. Because of the fundamental importance and potential applications of Majorana fermions, a variety of theoretical schemes have been proposed to realize Majorana corner modes in different experimental platforms. However, these schemes demand either unconventional superconducting pairings (p-wave, d-wave, etc.) or complicated junction/lattice structures, which are very difficult to implement with current experimental technologies.

Motivated by recent significant experimental progress on the realization of 2D quantum spin Hall insulators (QSHIs) in InAs/GaSb quantum wells and monolayer WTe₂, as well as the observation of their proximity effect with s-wave superconductors, we proposed a simple scheme to realize Majorana corner modes on such experimentally available QSHI/s-wave superconductor heterostructure by adding an additional ingredient: an in-plane Zeeman field. We showed that the in-plane Zeeman field plays a key role for inducing different topological effects on two adjacent edges, yielding Majorana corner modes at their intersection. We also extended the paradigm to 3D topological insulators and demonstrated the emergence of 1D Majorana hinge states. Avoiding complex superconductor pairing and material structure, our scheme provides a simple and experimentally realistic platform for implementing Majorana corner and hinge states.

Finally, the same experimental ingredient could also be realized in ultracold atomic gases.

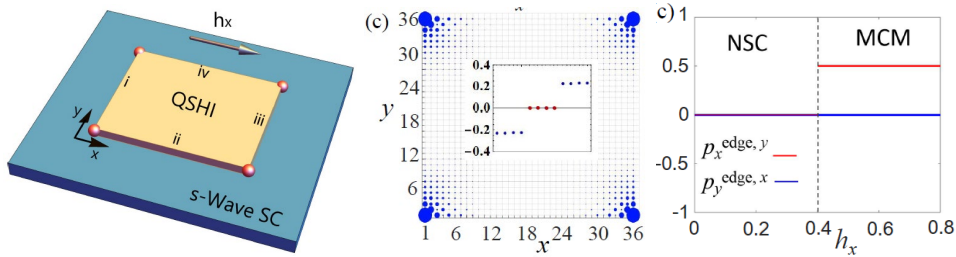


Figure 10: (Left) Illustration of a heterostructure composing of a quantum spin Hall insulator on top of an s-wave superconductor and subject to an in-plane Zeeman field. The spheres at four corners represent four Majorana zero energy modes. (Middle) Majorana corner states on a square lattice. (Right) Topological phase transition with the quantized edge polarization.

2.11. Topological bands and triply-degenerate points in non-Hermitian hyperbolic metamaterials,

Junpeng Hou, Zhitong Li, Xi-Wang Luo, Qing Gu, **Chuanwei Zhang**,
Phys. Rev. Lett. 124, 073603 (2020).

Hyperbolic metamaterials (HMMs), an unusual class of electromagnetic metamaterials, have found important applications in various fields such as super-resolution microscopy, biosensing, lasing, etc., due to their distinctive optical properties. A surprising feature of HMMs found recently is that even continuous HMMs can possess topological edge modes, making them a unique platform for studying topological photonics in continuous media. Due to their non-Hermitian and continuum properties, standard topological band theory for Hermitian systems does not apply, while previous treatment based on equal frequency surface is incomplete and provides incorrect predictions in certain parameter regions.

We developed a topological band description for continuous HMMs that can be described by a non-Hermitian Hamiltonian formulated from Maxwell's equations. We found two types of three dimensional photonic triply-degenerate points with topological charges ± 2 and 0 induced by different symmetry-breaking fields. Three dimensional TDPs have only been studied in condensed matter materials and ultracold atomic gases, and our finding provides the first prediction of triply-degenerate points in photonic materials. Moreover, we found the vacuum band plays an important role for topological edge states and bulk-edge correspondence in HMMs because of the photonic nature. The work presented a general non-Hermitian topological band treatment of continuous HMMs and should pave the way for exploring interesting topological phases in photonic continua. The band theory may be applied to engineered hyperbolic band in ultracold atomic gases for the realization of novel topological hyperbolic cold atomic quantum matter.

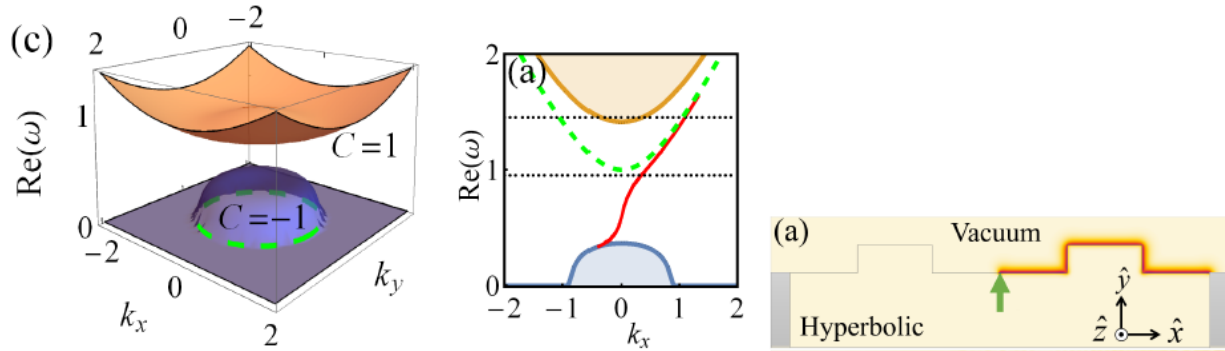


Figure 11: (Left) Topological band structure of the real part at a finite k_z . (Middle) Edge states in the presence of the vacuum band (green). (Right) Edge state through numerical simulation.

2.12: Supersymmetry-assisted high-fidelity ground-state preparation of a single neutral atom in an optical tweezer,

Xi-Wang Luo, Mark G. Raizen, Chuanwei Zhang,
Phys. Rev. A 103, 012415 (2021).

Neutral atoms trapped in optical tweezer arrays have emerged as a promising candidate for quantum computation and simulation due to their attractive features such as large scalability and high precision control and measurement. Despite experimental progress in the realization of high-fidelity single- and two-qubit gates, a major roadblock for realizing neutral atom quantum computation is the qubit initialization, which requires deterministic preparation of single atom on the vibrational ground state of an optical tweezer. For bosonic atoms, defect-free atom arrays with up to tens of single atoms have been demonstrated by rearranging the occupied tweezers. However, atoms in the tweezers are subject to imaging heating and the experimental ground-state cooling is far from perfect due to photon recoil in sideband cooling. For fermionic atoms, preparation of a single fermion ground state is possible through trap deformation, however, the trap need be tilted and ramped down to an extremely low depth, making the process very sensitive to external potential noises and requiring a long trap-deforming time. For both bosons and fermions, the fidelity to prepare a single atom in the ground state of a tweezer is only $\sim 90\%$ for realistic experiments.

In this paper, we proposed that supersymmetry—a theoretical framework developed in particle physics—can be used for ultra-high fidelity (~ 0.99999) initialization of neutral-atom qubits. We showed that a single atom can be deterministically prepared in the vibrational ground state of an optical tweezer by adiabatically extracting all excited atoms to a supersymmetric auxiliary tweezer. The scheme works for both bosonic and fermionic atom qubits trapped in realistic Gaussian optical tweezers. Our proposal can also be used to generate nonclassical quantum states with fixed atom number, which may find applications in other fields such as few-body physics, high-precision measurement and quantum sensors.

Our scheme is built upon recent experimental progress on single atom preparation and sideband cooling and applies to both fermion and boson qubits. It may pave the way for experimental realization of large-scale neutral atom quantum computation and simulation.

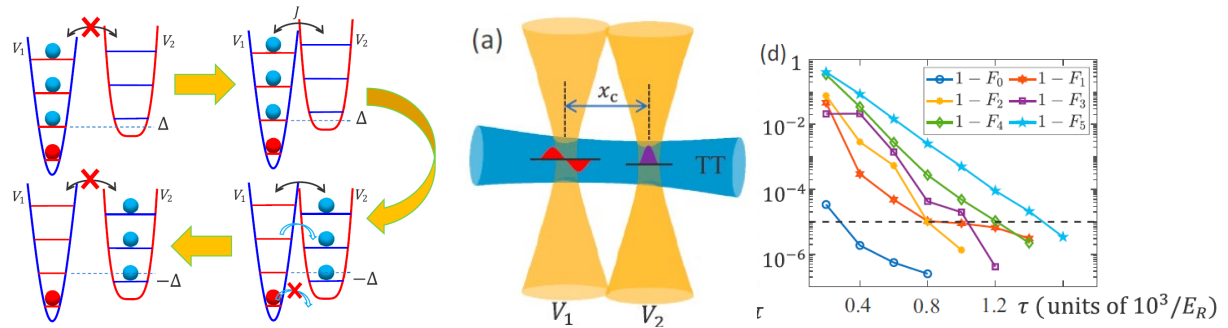


Figure 12: (Left) Scheme for extracting excited state atoms from main tweezer to its superpartner tweezer. (b) Laser setup. (c) Fidelity of the single qubit initialization.

2.13. Spin-twisted Optical Lattices: Tunable Flat Bands and Larkin-Ovchinnikov Superfluids,

Xi-Wang Luo, **Chuanwei Zhang**,
Phys. Rev. Lett. 126, 103201 (2021).

Moire superlattices in twisted bilayer graphene (TBG) and transition-metal dichalcogenides have emerged as a powerful tool for engineering novel band structures and quantum many-body phases of two-dimensional quantum materials. In TBG, the interactions, the inter- and intra-layer couplings are generally fixed with very limited tunability, and magic flat bands occur only in a narrow range of very small twist angles around $\sim 1.1^\circ$. Going beyond layer degree of freedom in TBG, two questions naturally arise. Can lattices of other pseudo degrees be twisted to realize novel Moire lattices with great tunability? If so, can new physics emerge in such twisted systems?

In this paper, we investigated Moire physics emerging from twisting two independent hexagonal optical lattices of atomic (pseudo-)spin states (instead of bilayers), which exhibits great tunability and remarkably different physics from twisted bilayer graphene. In our system, two spins reside on one layer spatially (instead of bilayer in TBG) with tunable coupling provided by additional lasers, resulting in different inter-spin (compared with inter-layer in TBG) hopping and other physical parameters. The interaction is dominated by the inter-spin s-wave scattering between atoms in relatively twisted spin lattices, in contrast to the intra-layer interaction without spin twist in TBG.

We employed a momentum-space tight-binding calculation that includes all range real-space tunneling and showed that all twist angles $\lesssim 6^\circ$ can become magic that support flat bands. Due to greatly enhanced density of states near the flat bands, the system can be driven to superfluid by weak attractive interaction. Surprisingly, the superfluid phase corresponds to a Larkin-Ovchinnikov state with finite momentum pairing, resulting from the interplay between inter-spin interactions and flat bands in the unique single-layer spin-twisted lattices.

In summary, we studied the Moire flat band physics and the associated superfluid order in spin-twisted optical lattices for ultracold atoms, which showcase remarkably different physics from twisted bilayer graphene. Our work opens a new playfield for studying many-body quantum phases with new types of twisted pseudospin degrees of freedom.

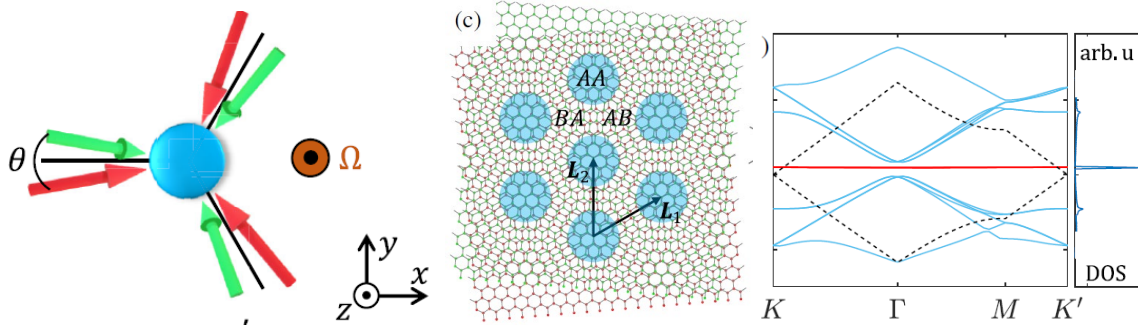


Figure 13: (Left) Laser setup for realizing twisted optical lattices. (Middle) Resulting Moiré lattice pattern. (Right) Flat band dispersion of Moire lattice.

2.14: Nonlinear dynamics in a synthetic momentum state lattice

Fangzhao Alex An, Bhuvanesh Sundar, Junpeng Hou, Xi-Wang Luo, Eric J. Meier, Chuanwei Zhang, Kaden R. A. Hazzard, Bryce Gadway,
Phys. Rev. Lett. [127.130401 \(2021\)](#) Editors' Suggestions

The scope of analog simulation in atomic, molecular, and optical systems has expanded greatly over the past decades. Recently, the idea of synthetic dimensions -- in which transport occurs in a space spanned by internal or motional states coupled by field-driven transitions -- has played a key role in this expansion. While approaches based on synthetic dimensions have led to rapid advances in single-particle Hamiltonian engineering, strong interaction effects have been conspicuously absent from most synthetic dimensions platforms. Here, in a lattice of coupled atomic momentum states, we showed that atomic interactions result in large and qualitative changes to dynamics in the synthetic dimension. We explored how the interplay of nonlinear interactions and coherent tunneling enriches the dynamics of a one-band tight-binding model, giving rise to macroscopic self-trapping and phase-driven Josephson dynamics with a nonsinusoidal current-phase relationship, which can be viewed as stemming from a nonlinear band structure arising from interactions.

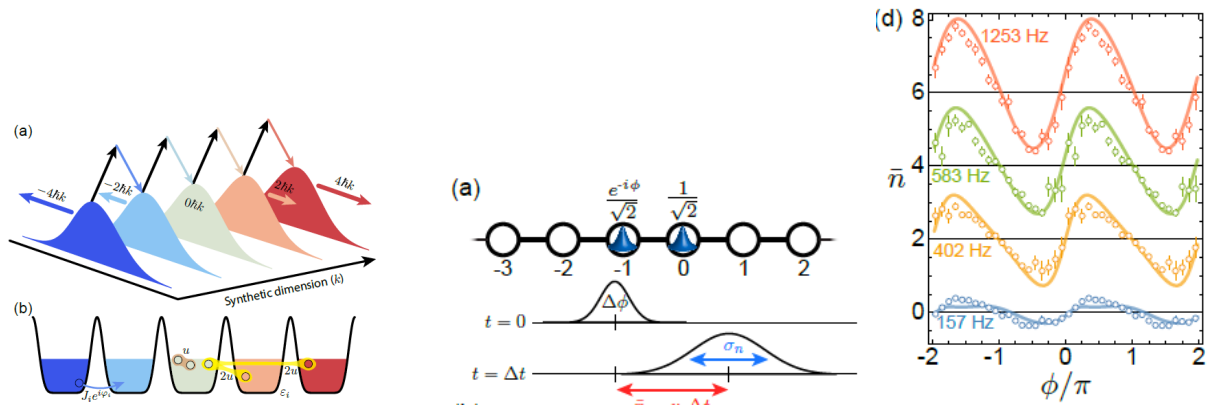


Figure 14: (Left) Illustration of synthetic momentum state lattices with atom-atom interactions. (Middle) Illustration of the phase-driven dynamics in a synthetic bosonic Josephson junction array. (Right) Plot of the oscillation of the wavepacket position with respect to the driven phase.

2.15: Observation of Many-body Dynamical Delocalization in a Kicked Ultracold Gas
Jun Hui See Toh, Katherine C. McCormick, Xinxin Tang, Ying Su, Xi-Wang Luo, Chuanwei Zhang, and Subhadeep Gupta
Nature Physics 18, 1297 (2022)

Contrary to a driven classical system that exhibits chaos phenomena and diffusive energy growth, a driven quantum system can exhibit dynamical localization that features energy saturation. However, the evolution of the dynamically localized state in the presence of many-body interactions has for long remained an open question. Here we realized a many-body quantum kicked rotor with a 1D ultracold gas periodically kicked by a pulsed optical lattice, and observed the interaction-driven emergence of dynamical delocalization. The dynamics feature a sub-diffusive energy growth which is manifest over a broad parameter range of interaction strengths and kick strengths. This observed onset of many-body quantum chaos and its characterization by the accompanying theoretical modeling introduce new tools to study many-body localization-delocalization phenomena in the synthetic momentum space.

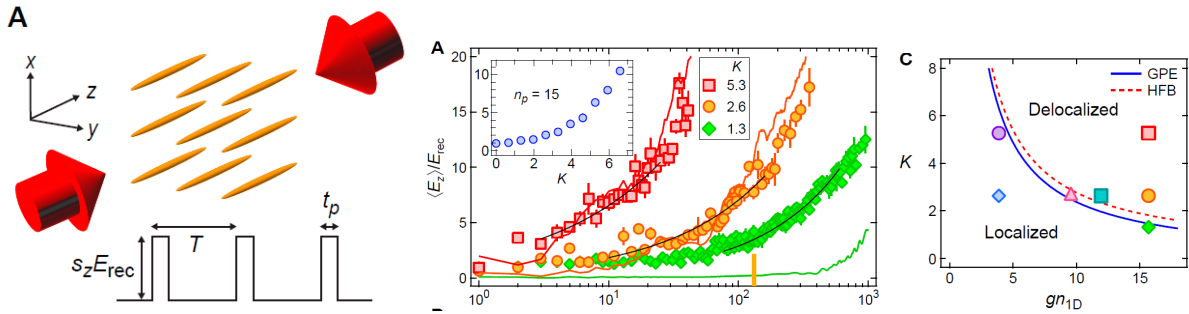


Figure 15: (Left panel) Illustration of the experimental setup. (Middle) Observation of the many-body delocalization with the subdiffusion of the energy. (Right) The Phase diagram between localized and delocalized phases.

2.16. Quantum squeezing and sensing with pseudo anti-parity-time symmetry

Xi-Wang Luo, Chuanwei Zhang, Shengwang Du,
Phys. Rev. Lett. **128**, 173602 (2022)

Parity Time ($\mathcal{PT}$) symmetry exhibits purely real eigenspectrum of non-Hermitian systems and unique phase transition physics across exceptional point, leading to not only fundamentally new physics but also technologically important applications that may not exist in Hermitian systems. In the past decade, significant progress has been made for exploring $\mathcal{PT}$ -symmetry physics in various physical systems (e.g., photonics, acoustics, ultracold atoms, etc.), which generally utilize the control of gain/loss in classical wave systems. However, an intrinsic obstacle for studying $\mathcal{PT}$ -symmetry physics in the quantum realm is that a $\mathcal{PT}$ -symmetric Hamiltonian involving gain/loss does not preserve the commutation relationships of quantum operators, therefore Langevin noises, which break $\mathcal{PT}$ symmetry, must be included in quantum systems.

Anti- $\mathcal{PT}$ ($\mathcal{APT}$) symmetry, a non-Hermitian symmetry with the Hamiltonian anticommuting with $\mathcal{PT}$ operator, does not have to involve gain/loss of classical fields, making it possible to realize a quantum $\mathcal{APT}$ -symmetry without Langevin noises. In this Letter, we construct the first quantum pseudo-anti-PT (pseudo- $\mathcal{APT}$) symmetry in a two-mode bosonic system without involving Langevin noises. We show that the pseudo- $\mathcal{APT}$ phase transition across the exceptional point yields a transition between different types of quantum squeezing behaviors, i.e., the squeezing factor increases exponentially (oscillates periodically) with time in the pseudo- $\mathcal{APT}$ symmetric (broken) region. Such dramatic changes of squeezing factors and associated quantum states near the exceptional point are utilized for ultra-precision quantum sensing with divergent sensitivity. We show that these exotic quantum phenomena and sensing applications induced by quantum pseudo- $\mathcal{APT}$ symmetry can be experimentally observed in two physical systems: spontaneous wave mixing nonlinear optics and atomic Bose-Einstein condensates.

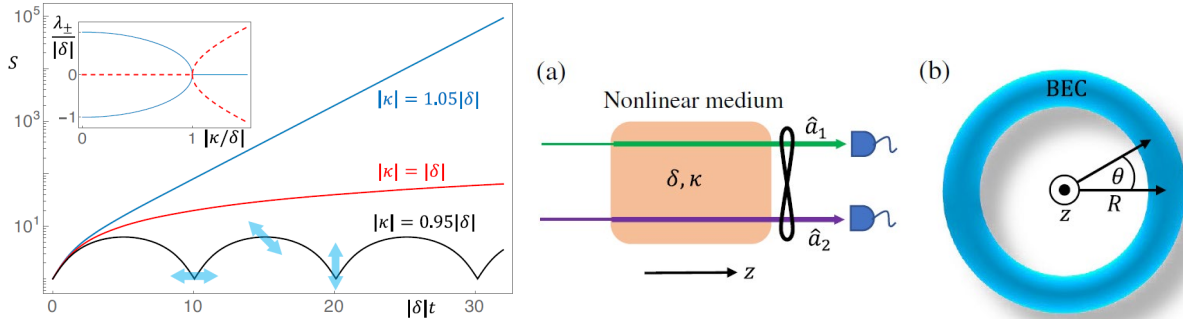


Figure 16: (Left) Pseudo-APT symmetry induced quantum squeezing dynamics. The figure shows the squeezing factor versus evolution time for different κ . (Right) Two proposed experimental implementations. (a) Schematic optical setup for realizing pseudo-APT -symmetry physics through nonlinear spontaneous four-wave mixing. (b) Experimental realization based on a cold atomic BEC in a ring trap.

3: Publications supported by ARO

- Underlined authors: graduate students and postdoctoral associates advised by the PI
 - *Corresponding authors
 - 49 published, including 2 Nature Physics, 4 Nature Communications, 1 Physical Review X, 13 Phys. Rev. Lett. (2 as Editors' suggestions).
1. Junpeng Hou, Xi-Wang Luo, Kuei Sun, **Chuanwei Zhang***, *Adiabatically tuning quantized supercurrents in an annular Bose-Einstein condensate*,
[Phys. Rev. A \(Rapid Communications\) 96, 011603 \(2017\).](#)
 2. Xi-Wang Luo, Xingxiang Zhou, Jin-Shi Xu, Chuan-Feng Li, Guang-Can Guo, **Chuanwei Zhang**, Zheng-Wei Zhou, *Synthetic-lattice enabled all-optical devices based on orbital angular momentum of light*,
[Nature Communications 8, 16097 \(2017\).](#)
 3. Abraham J. Olson, David B. Blasing, Chunlei Qu, Chuan-Hsun Li, Robert J. Niffenegger, **Chuanwei Zhang**, and Yong P. Chen, *Stueckelberg interferometry using periodically driven spin-orbit-coupled Bose-Einstein condensates*
[Phys. Rev. A 95, 043623 \(2017\)](#)
 4. Xi-Wang Luo, Kuei Sun, **Chuanwei Zhang***, *Spin-tensor--momentum-coupled Bose-Einstein condensates*,
[Phys. Rev. Lett. 119, 193001 \(2017\).](#)
 5. Mi Yan, Yinyin Qian, Hoi-Yin Hui, Ming Gong, **Chuanwei Zhang***, Vito W. Scarola, *Spin-Orbit Driven Transitions Between Mott Insulators and Finite Momentum Superfluids of Bosons in Optical Lattices*,
[Phys. Rev. A 96, 053619 \(2017\).](#)
 6. Xi-Wang Luo, **Chuanwei Zhang***, Guang-Can Guo, Zheng-Wei Zhou*, *Topological photonic orbital angular momentum switch*,
[Phys. Rev. A 97, 043841 \(2018\).](#)
 7. Lianghui Huang, Peng Peng, Donghao Li, Zengming Meng, Liangchao Chen, Chunlei Qu, Pengjun Wang, **Chuanwei Zhang***, Jing Zhang*, *Observation of Floquet band change in driven ultracold Fermi gases*,
[Phys. Rev. A 98, 013615 \(2018\).](#)
 8. Junpeng Hou, Haiping Hu, Kuei Sun, **Chuanwei Zhang***, *Superfluid quasicrystal in a Bose-Einstein Condensate*,
[Phys. Rev. Lett. 120, 060407 \(2018\)](#)
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 9. Chunlei Qu, **Chuanwei Zhang**, Fan Zhang*, *Valley-Selective Topological Ordered States in Irradiated Bilayer Graphene*,
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 10. Junpeng Hou, Xi-Wang Luo, Kuei Sun, Thomas Bersano, Vandna Gokhroo, Sean Mossman, Peter Engels, **Chuanwei Zhang***, *Momentum Space Josephson Effects*
[Phys. Rev. Lett. 120, 120401 \(2018\). PRL Editors' Suggestions](#)

11. Xi-Wang Luo, **Chuanwei Zhang***, *Self-adapted Floquet Dynamics of Ultracold Bosons in a Cavity*,
[Phys. Rev. Lett. 120, 263202 \(2018\)](#)
12. Haiping Hu, Junpeng Hou, Fan Zhang, **Chuanwei Zhang***, *Topological Triply-Degenerate Points Induced by Spin-Tensor-Momentum Couplings*,
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13. Matthew Maisberger, Lin-Cheng Wang, Kuei Sun, Yong Xu, **Chuanwei Zhang***, *Time-reversal-invariant spin-orbit-coupled bilayer Bose-Einstein Condensates*,
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14. Haiping Hu, **Chuanwei Zhang***, *Spin-1 Topological Monopoles in Parameter Space of Ultracold Atoms*,
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IV: Invited talks

1. *Topological lasing and quantum sensing with non-Hermitian symmetry*, 6th International Workshop on Quantum Coherence, Information, and Computing, Oct 2022, Hoboken, NJ
2. *Spin-Twisted Optical Lattices*, AFOSR meeting, August 2022, Arlington, VA
3. *Quantum technologies with ultracold atoms and lights*, College of Optical Sciences Colloquium, June 2021, University of Arizona, Tucson, Arizona
4. *Quantum technologies with atoms and solids*, Physics colloquium, Feb 2021, Emory University, Atlanta, GA
5. *Quantum technologies with atoms and solids*, Physics seminar, Feb 2021, Bowling Green State University, Bowling Green, Ohio
6. *Quantum Phases and Dynamics in Ultracold Atomic Gases*, ARO program review, Jan 2020, Durham, NC
7. *Quantum Technology with Ultracold Atoms, Photonics, & Solids*, Texas Quantum Institute Kick-off meeting, October 2019, College Station, TX
8. *Quantum Computation, Simulation and Metrology with Ultracold Atoms*, Texas Quantum Institute Kick-off meeting, October 2019, College Station, TX
9. *Spin-Tensor Momentum Coupling in Ultra-cold Atoms and Photonics*, Kavli Institute of Science workshop, June 2019, Beijing, China
10. *Topological triply-degenerate points in ultracold atoms and photonics*, Tsinghua University, June 2019, Beijing, China
11. *Topological triply-degenerate points in ultracold atoms and photonic hyperbolic metamaterials*, APS March meeting invited talk, March 2019, Boston, MA
12. *Quantum Phases and Dynamics of Driven Ultracold Atomic Gases*, ARO program review meeting, November 2018, Raleigh, NC
13. *Spin-Tensor Momentum Coupling in Ultra-cold Atoms and Photonics*, Condensed matter seminar, Washington University, October 2018, St Louis, MO

14. *Spin-Tensor-Momentum Coupling in Ultra-cold Atomic Gases*, AFOSR program review meeting, June 2018, Arlington, VA
15. *Topological quantum computation*, University of Science and Technology of China, June 2018, Hefei, China
16. *Spin-orbit coupled ultra-cold atomic gases*, ARO program review meeting, June 2017, Cocoa Beach, FL

V. Opportunities for training, development and mentoring

Research is a crucial part of science education at both graduate and undergraduate levels, and the involvement of students in research activities is an integral part of the proposed work. In the summers of 2018-2022, the PI hosted four REU students: Xingyi Wang (female) from Reed College (2018), Owen Tower (male) from University of Massachusetts at Dartmouth (2019), Quincy Webb (female) from Smith College (2020), and Luke Elder (male) from Roanoke College (2022). Xingyi worked with the PI and graduate student Junpeng Hou on a project about superstripe phases in a spin-orbit coupled Bose-Einstein condensate. Owen and Quincy worked with the PI, Prof. Kolodrubetz, and Junpeng Hou on a project about statistical quantum information processing. Luke worked with the PI on the quantum dynamics and phases in a non-Hermitian system.

The PI supervised six physics graduate students Matthew Maisberger, Mohammad M Mahmud, Junpeng Hou, Mengxin Du, Samyak Shrestha, and Arunaday Gupta during the grant period. Matthew Maisberger received his PhD in Dec 2020 and joined J. P. Morgan Chase as a Data Scientist. Junpeng Hou received his PhD in August 2021 and joined Facebook research as a research scientist. Mengxin has made important progress toward his PhD thesis. Samyak and Arunaday just started. The PI has supervised them on a daily basis to accomplish these projects. The synergistic combination of various numerical and analytic techniques in the proposed research promotes the interaction between students and the PI as well as the postdoctoral research associates in the group. As part of their training, students have presented their work at department seminars and major scientific conferences (e.g., APS March meeting and DAMOP meeting) to develop their communication skills. My former PhD student, Chunlei Qu (PhD 2015), joined Stevens Institute of Technology as an Assistant Professor in the Spring 2020.

Several postdoctoral research associates (Xiwang Luo, Ying Su, Haiping Hu, Yunmei Li) played an important role in some grant-related activities. They have helped the PI mentor graduate students on the daily basis, which is considered as a part of their training so that they are familiar with the student mentoring process after they become independent faculty in the future. The PI's mentorship to postdoctoral associates focuses on the development of their independent research projects, effective scientific presentations (both oral and written), broadening their research visions, etc.

The PI taught Quantum Mechanics II for graduate students in Spring 2019-2022 and Quantum Computing for undergraduate and graduate students in Fall 2018 and 2021. He also taught Quantum algorithm and software in Fall 2022. In addition to teaching physical principles in this course, the PI has made initial efforts to integrate state-of-art research related to course topics into lectures, with the purposes to enhance students' interest in AMO and condensed matter research and also to encourage them to undertake hands-on research. I worked with each student individually to pick an active research topic in condensed matter and cold atoms physics and develop some interesting research projects for them. All these activities expose the students to the frontier of cold atoms and condensed matter research and the students are very excited about that.