



Novel Quantum Matter in Ultra-cold Atomic Gases with Synthetic Spin-orbit Coupling

Chuanwei Zhang
UNIVERSITY OF TEXAS AT DALLAS

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Final Report

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1. Abstract

Spin-orbit coupling has played important roles in condensed matter as well as atomic and nuclear physics. In this context, the recent experimental realization of the coupling between spin and linear momentum (SLM coupling) of ultra-cold atoms provides a completely new avenue for exploring many-body phenomena using atomic superfluids. On the other hand, many other important and fundamental types of spin-orbit coupling, such as the coupling between spin and orbital angular momentum (SOAM coupling) have not been explored for cold atoms. Moreover, the experimental realization of SLM coupling has only utilized the lowest order Gaussian laser beams. The objective of the proposal is to investigate new quantum phases derived from synthetic SLM and SOAM coupling, with particular emphasis on their experimental relevance. The proposed work will give theoretical insights of the generation and application of various types of SLM and SOAM coupling in cold atom superfluids, which will not only pave the way for their experimental realization, but also provides a platform for engineering novel quantum matter. In the past two years, two experimental groups have realized our proposed SOAM coupling and observed the resulting phase transition.

Our main research activities during the funding period include:

- 1) Collaborated with Jing Zhang's experimental group (Shanxi University), we observed the 2D SLM coupling with a perpendicular Zeeman field, which opens a topological band gap at the Dirac point, paving the way for the observation of topological superfluids with Majorana and Weyl fermionic excitations (Phys. Rev. Lett. 117, 235304 (2016) PRL Editors' Suggestions). We also directly measured Floquet band dispersions in a periodically driven SLM coupled ultracold Fermi gas. Using spin injection radio-frequency spectroscopy, we observed that the Dirac point originating from 2D SLM 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 (Phys. Rev. A 98, 013615 (2018))
- 2) We showed that arbitrary quantized circulation states can be adiabatically prepared and tuned as the ground state of a ring-shaped BEC by utilizing SOAM coupling and an external potential. The work provides a powerful platform for studying SOAM-coupled ultracold atomic gases and building atomtronic circuits. (Phys. Rev. A (Rapid Communications) 96, 011603 (2017))
- 3) In previous studies of SLM coupling, spin usually represents spin vector (spin-1/2 or spin-1). We proposed a scheme to realize a new type of spin-tensor--momentum coupling (STMC) in spin-1 ultracold atomic gases (Phys. Rev. Lett. 119, 193001 (2017)) and studied their exotic properties for both Bosons and Fermions such as supersolid stripes (Phys. Rev. A 100, 063606 (2019)), topological triply-degenerate fermions (Phys. Rev. Lett. 120, 240401 (2018); Phys. Rev. A 98, 013627 (2018)), magnetic stripe solitons (Phys. Rev. A 101, 023621 (2020)), quantum spiral spin-tensor magnetism (Phys. Rev. B (Rapid Communications) 101, 140412 (2020)).
- 4) We studied the manipulation of photon orbital angular momentum (OAM) in a cavity, which provides a synthetic dimension for engineering many new types of all-optical devices (Nature Communications 8, 16097 (2017)), including a topological photonic OAM switch (Phys. Rev. A 97, 043841 (2018)).

- 5) As an analogy to super-solids, we proposed a new quantum state named super-quasicrystal that possesses both superfluid and quasi-crystalline orders and show that it can be realized with a simple experimental setup. Our study will advance our understanding of both quasicrystals and superfluids and open a significant new area of research: superfluid-quasicrystals (Phys. Rev. Lett. 120, 060407 (2018)).
- 6) Time-reversal-invariant topological superfluids are exotic states of matter possessing Majorana Kramers pairs (MKPs), yet their realizations have long been hindered by the requirement of unconventional pairing. We proposed to realize such a topological superfluid by utilizing *s*-wave pairing and emergent symmetries in two coupled 1D ultracold atomic Fermi gases with spin-orbit coupling (Phys. Rev. Lett. 121, 185302 (2018); Phys. Rev. A 97, 053624 (2018)). The key gradient of the scheme is to use Hermite-Gaussian beams for the Raman coupling in the realization of spin-orbit coupling.
- 7) We proposed to realize the Josephson effects in the momentum space by coupling two band minima of a spin-orbit coupled BEC (Phys. Rev. Lett. 120, 120401 (2018), PRL Editors' Suggestions). 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 (Phys. Rev. A 99, 051602(R) (2019)).
- 8) Collaborated with Peter Engels' experimental group, we theoretically conceived and experimentally demonstrated 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. 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 spintronic and atomtronic devices (Nature Communications 10, 3381 (2019), Selected as monthly Editors' Highlights for Nature Communications).
- 9) Collaborated with Yong Chen's experimental group, we explored the effects of synthetic SLM coupling and atomic interactions on the spin transport in an atomic Bose-Einstein condensate (BEC). We experimentally observed that SLM coupling significantly enhances the spin current damping while reducing the thermalization (Nature Communications 10, 375 (2019)).
- 10) Higher-order topological insulators are topological phases that exhibit novel boundary states on corners or hinges. We showed that higher-order topological corner states can emerge by introducing staggered on-site gain and loss to a Hermitian system in a trivial phase. Such gain- and loss-induced higher-order topological corner states can be experimentally realized using photons in coupled cavities or cold atoms in optical lattices (Phys. Rev. Lett. 123, 073601 (2019)).
- 11) The realization of second-order Majorana corner modes usually demands unconventional superconducting pairing or complicated junctions/layered structures. We showed 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. Avoiding complex superconductor pairing and material structure, our scheme provides an experimentally realistic platform for implementing Majorana corner and hinge states (arXiv:1905.08896, Phys. Rev. Lett. in press).

- 12) Hyperbolic metamaterials (HMMs), an unusual class of electromagnetic metamaterials, have found important applications in various fields due to their distinctive properties. 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 non-Hermitian triply degenerate points with complex linear dispersions and topological charges 2 and 0. Our work presents a general non-Hermitian topological band treatment of continuous HMMs, paving the way for exploring interesting topological phases in photonic continua and device implementations of topological HMMs ([Phys. Rev. Lett. 124, 073603 \(2020\)](#)).
- 13) Spin Hall effect (SHE), a fundamental transport phenomenon with non-zero spin current but vanishing charge current, has important applications in spintronics for the electrical control of spins. Owing to the half-spin nature of electrons, the rank of spin current (determined by the rank of spin tensor) has been restricted to 0 and 1 for charge and spin Hall effects. We introduced and characterized higher-rank (≥ 2) SHEs in large spin (≥ 1) systems. We found a universal rank-2 spin Hall conductivity $e/4\pi$ (with zero rank-0 and 1 conductivities) for a spin-1 model with intrinsic spin-orbit (SO) coupling. An experimental scheme is proposed to realize the required SO coupling for rank-2 SHEs with pseudospin-1 fermionic atoms in an optical lattice ([arXiv:2001.08675](#)).

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. In the following we describe several major research findings in the funding period resulted from the PI's research activities.

2.1. 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.

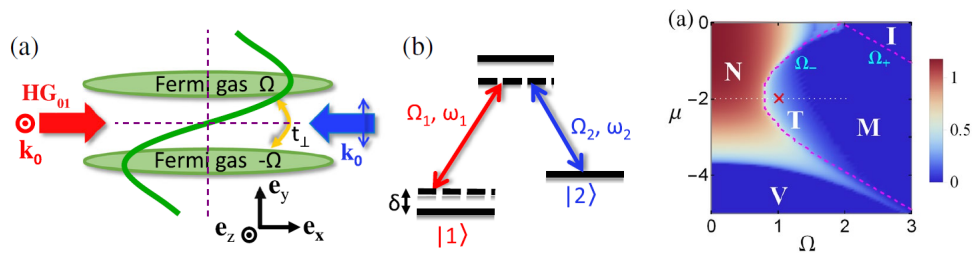


Figure 1: (Left) Proposed experimental setup for realizing time-reversal invariant two chain system. (Middle) Raman laser configuration. (Right) The phase diagram for the topological superfluids with MKPs.

2.2: 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.

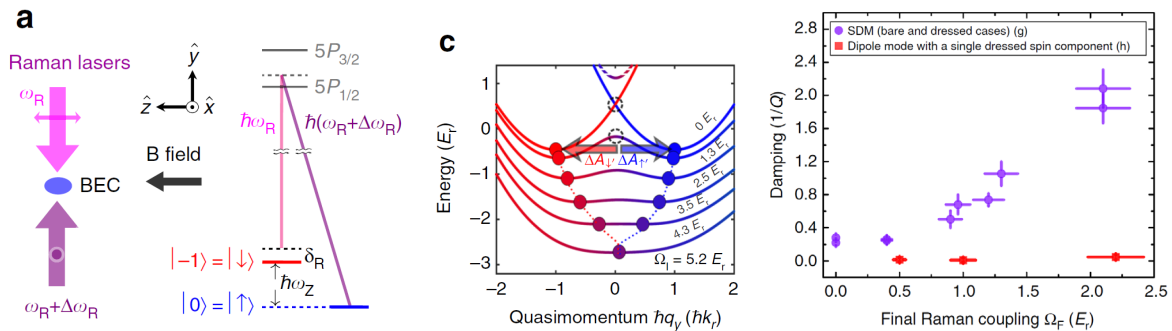


Figure 2: (Left) Experimental setup for generating spin-orbit coupling for Rb87 atoms. (Middle) Generation of spin-dependent gauge electric field through quenching Raman coupling strength. (c) Observed spin damping due to spin collision.

2.3. 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.

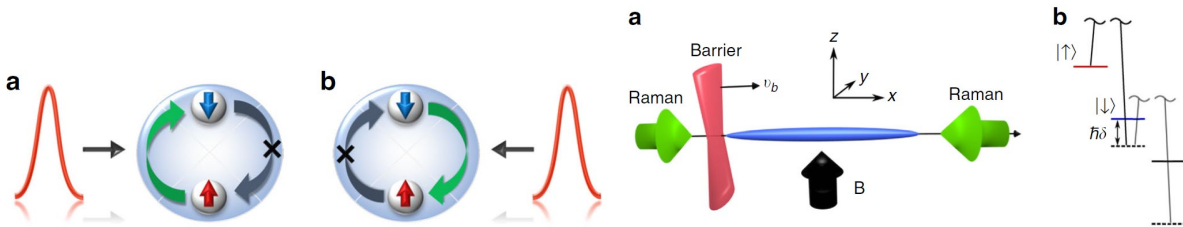


Figure 3: (Left panel): General concept and mechanism of a one-way spin switch. A control signal incoming from **a** the left or **b** the right is able to switch the spin orientation of the system from \uparrow to \downarrow (**a**) or \downarrow to \uparrow (**b**) while the reverse processes are forbidden. (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.

2.4: 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.

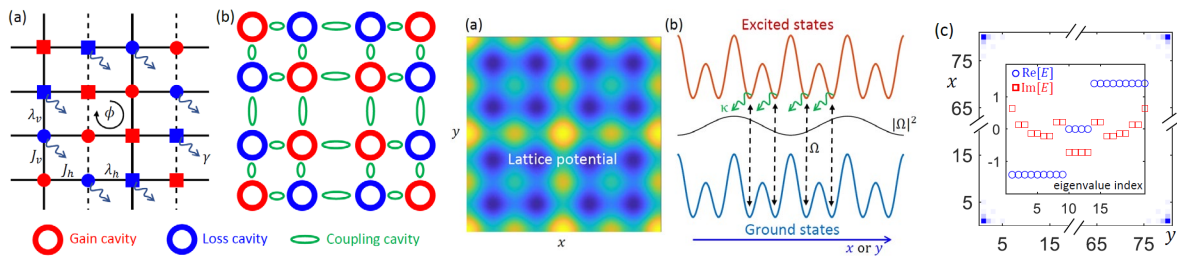


Figure 4: (Left panel) (a) Lattice representation of the non-Hermitian model. All sites in blue (red) have particle loss (gain) with a rate γ . (b) Experimental implementation of the lattice model in (a) using coupled arrays of micro-ring cavities. (Middle panel) Proposed experimental realization using cold atoms in optical lattices. (Right panel) Topological corner states in a 2D lattice.

2.5: 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, [arXiv:1905.08896](https://arxiv.org/abs/1905.08896), to appear in *Phys. Rev. Lett.*

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.

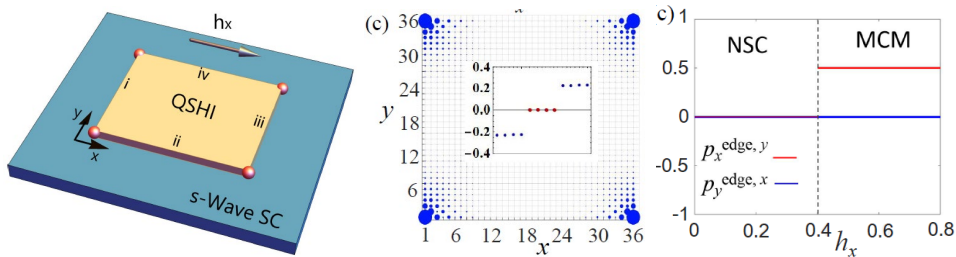


Figure 5: (Left) Illustration of a heterostructure composing of a quantum spin Hall insulator on top of an s-wave superconductor and subject to an in-plane Zeeman field. The spheres at four corners represent four Majorana zero energy modes. (Middle) Majorana corner states on a square lattice. (Right) Topological phase transition with the quantized edge polarization.

2.6: 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.

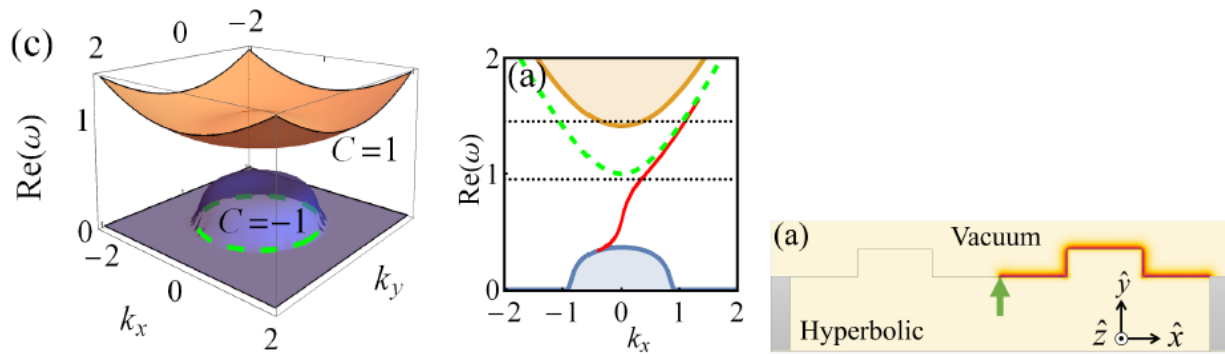


Figure 6: (Left) Topological band structure of the real part at a finite k_z . (Middle) Edge states in the presence of the vacuum band (green). (Right) Edge state through numerical simulation.

2.7. 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.

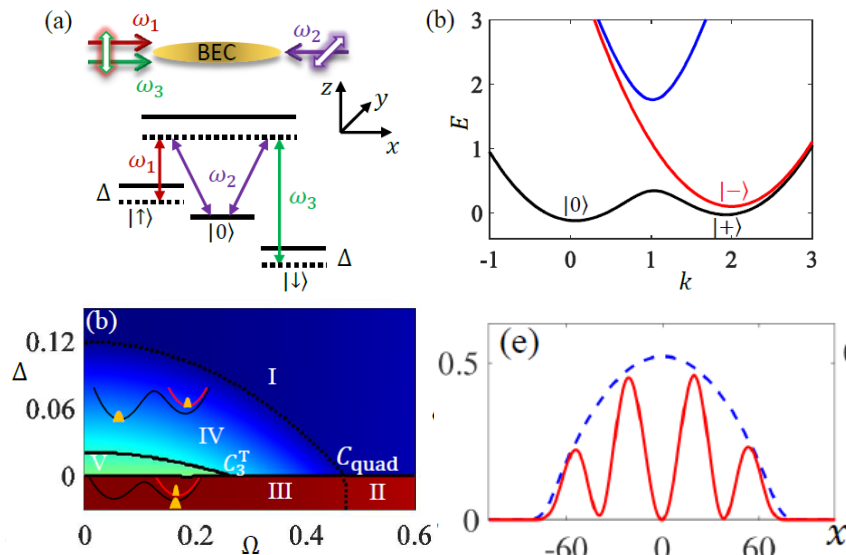


Figure 7: (Top) Proposed experimental setup and resulting band structure. (Bottom) Ground state phase diagram and the dynamical stripe phases.

2.8. 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.

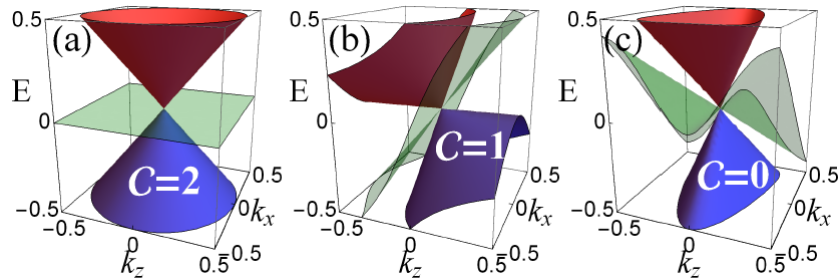


Figure 8: Three types of triply-degenerate points with different Chern numbers induced by spin-tensor momentum couplings.

2.9: 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 superfluid quasicrystal 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.

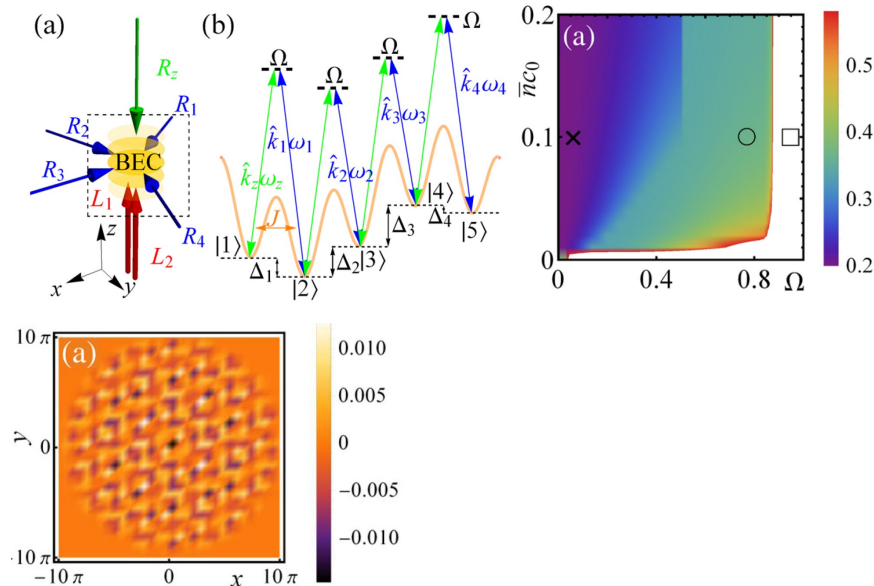


Figure 9: (Top Left) Proposed experimental scheme for generating superfluid quasicrystals. (Top right) phase diagram. (c) Real space density distribution for a superfluid quasicrystal in a harmonic trap.

2.10: 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.

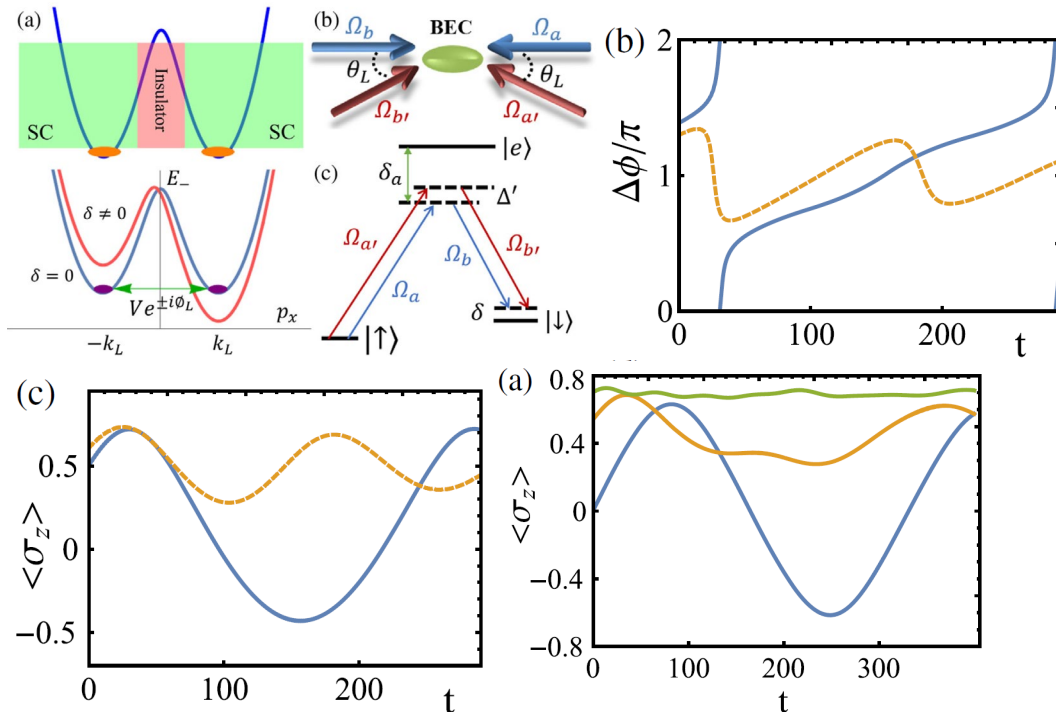


Figure 10: (Top Left) Proposed experimental scheme for realizing momentum space Josephson effect in a spin-orbit coupled ultra-cold atomic gas. (Top right) The phase oscillation for Josephson effect. (Bottom left) The spin polarization oscillation for weak interaction. (Bottom right) The spin polarization oscillation for strong interaction.

2.11: 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.

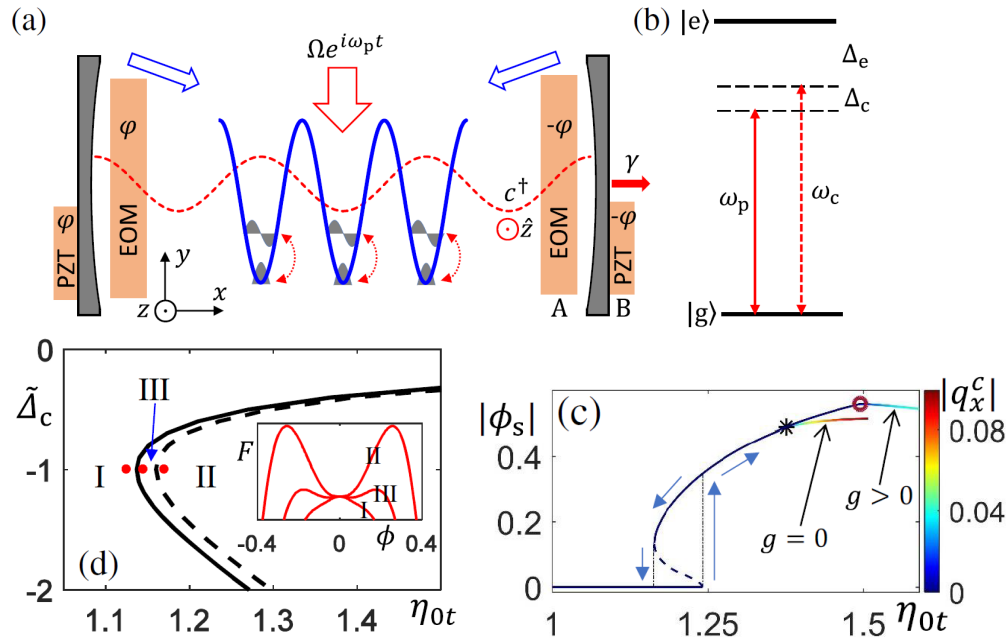


Figure 11: (Top) Experimental setup. (Bottom) Phase diagram and hysteresis phenomenon.

2.12: Experimental observation of topological band gap opening in ultracold Fermi gases with two-dimensional spin-orbit coupling

Zengming Meng, Lianghai Huang, Peng Peng, Donghao Li, Liangchao Chen, Yong Xu, Chuanwei Zhang, Pengjun Wang, and Jing Zhang,
 Phys. Rev. Lett. 117, 235304 (2016) PRL Editors' Suggestions

Spin-orbit coupling (SOC) and Zeeman fields are crucial ingredients for many topological quantum matters. In this context, the recent experimental realization of synthetic SOC, both one-dimensional (1D) and two-dimensional (2D), opens a new avenue for exploring topological states with ultracold atoms. However, in 2D SOC (e.g., Rashba type), a perpendicular Zeeman field, which opens a band gap at the Dirac point and induces topological properties, has not been realized in experiments for ultracold atoms. Here we propose and realize a simple scheme for generating 2D SOC and a perpendicular Zeeman field simultaneously in ultracold Fermi gases by tuning the polarization of three Raman lasers that couple three hyperfine ground states of atoms. The resulting band gap opening at the Dirac point is probed using spin injection radio-frequency spectroscopy. Our observation may pave the way for exploring topological transport and topological superfluids with exotic Majorana and Weyl fermion excitations in ultracold atoms.

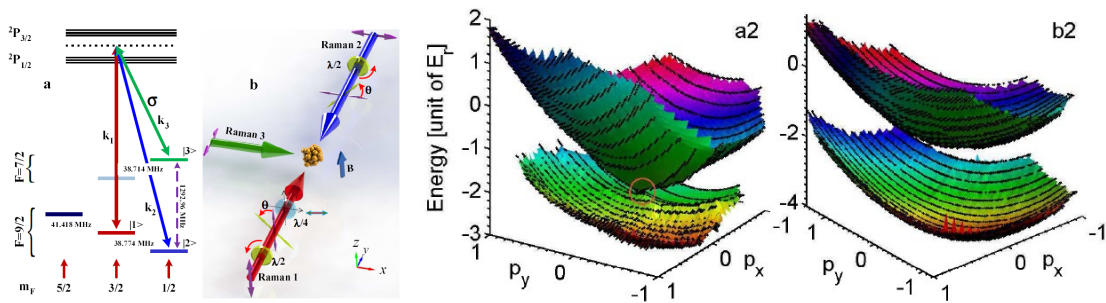


Figure 12: (Left) Level scheme and laser setup for the generation of 2D spin-orbit coupling and perpendicular Zeeman field. The half and quarter waveplates are used to change the phase of the Raman lasers which induces the perpendicular Zeeman field. (Middle) Dirac point without the perpendicular Zeeman field. (Right) topological band gap opening with the perpendicular Zeeman field.

2.13: Synthetic photonic lattices: new routes towards all-optical photonic devices
 Xi-Wang Luo, Xingxiang Zhou, Jin-Shi Xu, Chuan-Feng Li, Guang-Can Guo, Chuanwei Zhang,
 Zheng-Wei Zhou,
Nature Communications, 8, 16097 (2017).

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 photon 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 a single main degenerate cavity. The design route utilizing synthetic photonic lattices may significantly reduce the requirement for numerous optical elements and their fine tuning in conventional design, paving the way for realistic all-optical photonic devices with novel functionalities.

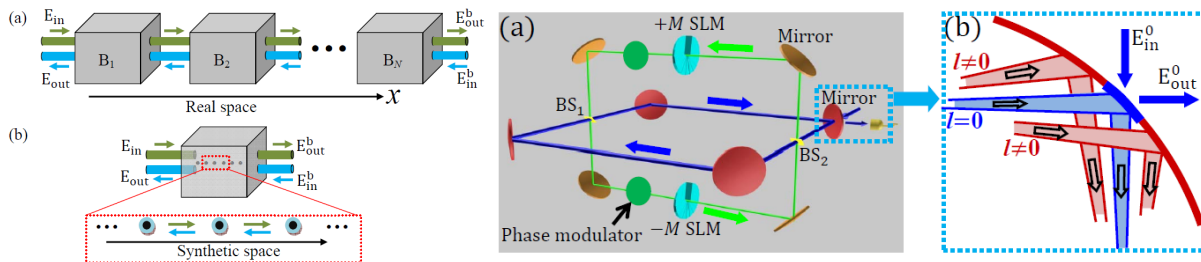


Figure 13: (left) Illustration of the design principle based on synthetic photonic lattices. (right) All-optical photonic devices based on a degenerate cavity system.

3. Conclusion

These research activities lead to 33 papers published and 9 submitted for publication in peer-reviewed journals, including 3 published in Nature Communications (1 selected as monthly Editors' Highlights), 1 in Phys. Rev. X, 11 in Physical Review Letters. Our work on spin current generation and relaxation has been reported by Science Daily. Our proposed SOAM coupling for ultracold atoms has been realized in experiments by two research groups. Our work on superfluid quasicrystals has been widely reported by various news media, including Newsweek magazine. Our research results were also presented in invited and contributed talks in various conferences. 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 AFOSR in the past.

In addition to these research activities, the AFOSR 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.

4: Publications supported by AFOSR

Underlined authors: graduate students and postdoctoral associates advised by the PI

* Corresponding authors

Nature Communications: 3

Physical Review X: 1

Physical Review Letters: 11

Physical Review A and B: 16

Europhysics Letters: 1

2D Materials: 1

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9. Xi-Wang Luo, **Chuanwei Zhang***, *Higher-order topological corner states induced by gain and loss*,
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14. Haiping Hu, Shu Chen, Tian-Sheng Zeng, **Chuanwei Zhang***, *Topological Mott Insulator with Bosonic Edge Modes in 1D Fermionic Superlattices*,
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18. Junpeng Hou, Haiping Hu, Kuei Sun, **Chuanwei Zhang***, *Superfluid quasicrystal in a Bose-Einstein Condensate*,
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[Eurekalert news](#)
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21. Xi-Wang Luo, **Chuanwei Zhang***, *Self-adapted Floquet Dynamics of Ultracold Bosons in a Cavity*,
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39. Xi-Wang Luo, **Chuanwei Zhang***, *Non-Hermitian Disorder-induced Topological Insulators*,
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5: Invited talks

1. *Quantum Phases and Dynamics in Ultracold Atomic Gases*, ARO program review meeting, Jan 2020, Durham, NC
2. *Quantum Computation, Simulation and Metrology with Ultracold Atoms*, Texas Quantum Institute kick-off meeting, October 2019, College Station, TX
3. *Spin-Tensor Momentum Coupling in Ultra-cold Atoms and Photonics*, Kavli Institute of Science workshop, June 2019, Beijing, China
4. *Topological triply-degenerate points in ultracold atoms and photonics*, Tsinghua University, June 2019, Beijing, China
5. *Topological triply-degenerate points in ultracold atoms and photonic hyperbolic metamaterials*, APS March meeting invited talk, March 2019, Boston, MA
6. *Quantum Phases and Dynamics of Driven Ultracold Atomic Gases*, ARO program review meeting, November 2018, Raleigh, NC
7. *Spin-Tensor Momentum Coupling in Ultra-cold Atoms and Photonics*, Condensed matter seminar, Washington University, October 2018, St Louis, MO
8. *Topological Quantum Computation and Majorana Fermions*, Public Lecture, in celebration of 60 Anniversary of University of Science and Technology of China, June 2018, Hefei, China
9. *Spin-Tensor Momentum Coupled Ultra-cold Atomic Gases*, Physics seminar, University of Science and Technology of China, June 2018, Hefei, China
10. *Spin-Tensor Momentum Coupled Ultra-cold Atomic Gases*, AFOSR program review meeting, June 2018, Arlington, VA
11. *Spin-orbit coupled ultra-cold atomic gases*, ARO program review meeting, June 2017, Cocoa Beach, FL