AFRL-AFOSR-VA-TR-2020-0165

Novel quantum magnetic, orbital and topological states with ultra-cold atoms

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06/05/2020
Final Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTB1
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
08-09-2020

2. REPORT TYPE
Final Performance

3. DATES COVERED *(From - To)*
15 Sep 2014 to 14 Mar 2020

4. TITLE AND SUBTITLE
Novel quantum magnetic, orbital and topological states with ultra-cold atoms

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-14-1-0168

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Congjun Wu

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
UNIVERSITY OF CALIFORNIA, SAN DIEGO
9500 GILMAN DR DEPT 621
LA JOLLA, CA 92093-0621 US

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR RTB1

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-VA-TR-2020-0165

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
First, we have systematically studied the thermodynamic and ground state properties of SU($2N$) fermions, which can be realized by alkaline-earth atoms, by performing large-scale quantum Monte-Carlo simulations. The thermal valence-bondsolid phase transition is found, and the Pomeranchuk effect, the density and spin susceptibilities are simulated. SU($2N$) Dirac fermions are simulated: Valence-bond-solid states are found in the SU(4) and SU(6) cases in contrast to the N'eel ordering in the SU(2) case. The SU(6)Hubbard model shows very different behavior from the well-studied SU(2) one. It exhibits the quantum magnetic transition from the antiferromagnetic state to the valance band solid phase as increasing the interaction strengths. Antiferromagnetism starts to develop in the weak interacting regime based on the Slater mechanism, and it is suppressed as U further increases, and then the valence-bond-solid phase appears. This work sheds light on the explorations of novel states of matter with ultra-cold large-spin alkaline fermions.

15. SUBJECT TERMS
novel quantum phases

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UU		METCALFE, GRACE
					19b. TELEPHONE NUMBER *(Include area code)* 703-696-9740

Final Report (2014-2020) to Dr. Grace Metcalfe

Congjun Wu, Department of Physics, UCSD

Contract/Grant
Title: Novel Quantum Magnetic, Orbital, and Topological States with Ultra-Cold Atoms
Contract/Grant # FA9550-14-1-0168

The AFOSR award (FA9550-14-1-0168) supported Congjun Wu's research during (Sept. 15 2014- Mar. 31, 2020). The work supported by this award has investigated novel quantum many-body states with ultra-cold atoms. Our results have greatly deepened our understanding and provide theoretical support for the study of novel states of matter with cold atoms.

Under the support from AFOSR, we have published 23 research papers in high profile research journals, including 4 published in *Physical Review Letters*, 1 published in *Physical Review X*, 1 published in *Nature*, and 1 review paper published in *Journal of Physics Condensed Matter*.

Below we present our progress under the support of this award. In Sect. 1, the research progress is presented with a few representative results are explained. The list of publications is given in Sect. 2. In Sect. 3, the education activity and human resource development are reported. In Sect. 4, invited talks at conferences, department seminars, physics colloquium are reported.

1 Research progress

1.1 Space-time crystal and space-time group

Motivated by the rapid progress of quantum dynamics, we recently constructed the space-time symmetry framework for quantum dynamic systems, which is published at **Phys. Rev. Lett. 120, 096401 (2018)**. Our results serve as a symmetry foundation for studying dynamic systems, including transport and topological properties. It is well-known that crystal symmetries and the Bloch theorem play a fundamental role in condensed matter physics. We extend the concept of static crystal to the dynamic space-time crystal characterized by the general intertwined space-time periodicities in D+1 dimensions, which include both the static crystal and the Floquet crystal as special cases. All of the basic concepts, including the Bloch theorem, bands, need to be generalized for intertwined space-time symmetries.

We invented a mathematical structure dubbed space-time group to describe the discrete symmetries of a space-time crystal. Compared to space and magnetic groups, space-time group is augmented by time-screw rotations and time-glide reflections involving fractional translations along the time direction. Similar to the crystal classification based on space groups, the classification of space-time crystal is based on space-time group. We performed complete classifications of 13 and 275 space-time groups for 1+1 D and 2+1D space-time crystals, respectively, in contrast to the 17 wallpaper space groups and 230 space groups for the 2D and 3D static crystals.

1.2 Quantum spin dynamics

One-dimensional (1D) integrable models due to their exact solvability provide a reliable reference for the study of quantum spin dynamics. The low energy fractional excitations of 1D integrable models are often well-understood, which can also be captured by the low energy effective field theory. However, exploring quantum dynamics remains challenging due to the interplay between quantum dynamic excitations and strong correlations. Recently, in collaboration with A. Loidles group in Germany, we provide the theory support for the experimental electron-spin-resonance measurement of quantum spin dynamics, which is published in **Nature, 554, 219 (2018)**. My group calculated the real frequency responses at high energy in strongly correlated systems, which is a hardcore problem of condensed matter physics, based on integrable methods **Phys. Rev. B 100, 184406 (2019)**.

Bethe string states are a class of exotic many-body excitations of high energy magnon anti-bound states merged in the sea of scattering states of unbound magnons. Our calculations are technically non-trivial based on the form-factor method, which was not done before for the XXZ model with the Ising anisotropy, and physically important for setting up benchmarks for the study of Bethe string states. Various excitations at different energy scales are identified crucial to the dynamic spin structure factors under the guidance of sum rules. At small magnetic polarizations, gapless excitations dominate the low energy spin dynamics arising from the magnetic-field-induced incommensurability. In contrast, spin dynamics at intermediate and high energies is characterized by the two- and three-string states, which are multi-particle excitations based on the commensurate Neel ordered background. Our work is helpful for experimental studies on spin dynamics in both condensed matter and cold atom systems beyond the low energy effective Luttinger liquid theory. Based on an intuitive physical picture, we speculate that the dynamic feature at high energies due to the multi-particle anti-bound state excitations can be generalized to non-integrable spin systems.

1.3 Novel states of bosons in the synthetic gauge field

The synthetic gauge field and spin-orbit coupling have become a major research interest of cold atom physics. My previous works arxiv:0809.3532 (**Chin. Phys. Lett. 28, 097102 (2011)**) and **Mod. Phys. Lett. 23, 1 (2009)** are ealy contributions to this field.

We continue to study the ground-state properties of the two-component spin-orbit-coupled ultracold bosons subject to a rotationally symmetric in-plane gradient magnetic field published at **PRA 91, 033603 (2015)**. Furthermore, we study topological condensates of bosons under the 3D early spin-orbit coupling published at **PRA 93, 033628 (2016)**. The usual boson superfluid breaks the U(1) symmetry, and the associated topological defects are vortices forming the 2D Abriksov vortex lattice state. We have found its non-Abelian generalizations in the two-component spinor boson systems under the Weyl-type spin-orbit coupling. It realizes a beautiful mathematical concept of Hopf mapping. The condensate topology manifests in the quaternionic representation. Spin textures evolve from the concentric distributions to the 3D skrymion lattice configurations as increasing spin-orbit coupling strength. Our states are a non-Abelian generalization of the ordinary Abrikosov vortex lattice states in three dimensions.

The magnetic monopole in the EM theory is a long-standing problem, and so far no convincing experiment evidence exists in the real world. We present a method to create synthetic monopole field in real space by applying the Floquet engineering of a magnetic quadrupole field, which is published in **Phys. Rev. Lett. 120, 130402 (2018)**. It leads to a flexible scheme to realize exact flat Landau levels on curved spherical geometry in a system of spinful cold atoms. We show that, within current technique, exact Landau levels on Haldanes spherical geometry can indeed be implemented in a highly controllable manner. By projecting the atom into the lowest-energy spin manifold, we confirm that the single-particle physics is mapped to an electronmonopole system on a sphere. We investigate the ground-state vortex pattern for an s-wave interacting atomic condensate by mapping this system to the classical Thompsons problem. The distortion and stability of the vortex pattern are further studied in the presence of the magnetic dipolar interaction. Our scheme is compatible with the current experimental setup, and may serve as a promising route of investigating quantum Hall physics and exotic spinor vortex matter on curved space.

1.4 The SU(2N) alkaline-earth fermions

The study of novel quantum phases of the large-hyperfine-spin alkali/alkaline-earth fermions has become an important research direction of ultra-cold atom physics. My previous work (**Phys. Rev. Lett. 91, 186402 (2003)**) was a pioneering paper proposing to investigate high symmetry properties of SU(2N) and Sp(2N) with alkali and alkaline-earth fermions.

During the period supported by this award, we performed a systematic study of thermodynamics of large spin fermions by using the non-perturbative method of quantum Monte-Carlo simulations. We have made further progress in calculating the entropy-temperature relation, the isoentropy curve, and the probability distribution of the onsite occupation number are calculated, which exhibit prominent features of the Pomeranchuk effect published in **Phys. Rev. B 90, 235139 (2014)**. This result provides important guidance to the cold atom experiments.

We have made progress on studying the strong correlation physics of SU(2N) Dirac fermions based on a π-flux square lattice, which is published at **Phys. Rev. B 97, 195122 (2018)**. With increasing repulsive interaction, we show that a Mott transition occurs from the semimetal to the valence bond solid, accompanied by the Z_4 discrete symmetry breaking based on sign-problem free quantum Monte-Carlo simulations. Our simulations demonstrate the existence of a second-order phase transition, which confirms the Ginzburg-Landau analysis. To account for the effect of a π-flux on the ordering in the strong-coupling regime, we analytically derive by the perturbation theory the ring-exchange term, which is the leading-order term that can reflect the difference between the π-flux and zero-flux SU(4) Hubbard models.

We have performed a systematic study of the interplay between charge and spin degrees of SU(2N) Dirac fermions, which is a long-standing problem in condensed matter physics, which is published at **PRB 93, 245157 (2016)**. We investigate the competing orders in the half-filled SU(2N) Hubbard model on a honeycomb lattice. Employing large-scale projector determinant quantum Monte Carlo simulations, we have explored quantum phase transitions from the gapless Dirac semimetals to the gapped Mott insulating phases in the SU(4) and SU(6) cases. Both of these Mott insulating states are found to be columnar valence bond solid (cVBS) and to be absent of the antiferromagnetic Neel ordering and the loop current ordering. Inside the cVBS phases, the dimer ordering is enhanced by increasing fermion components and behaves non-monotonically as the interaction strength increases.

We perform the large scale projector determinant quantum Monte-Carlo simulations to study the insulating states of the half-filled SU(6) Hubbard model on the square lattice published in **Phys. Rev. B 100, 115155 (2019)**. Typically speaking, there are two different mechanisms for insulating states: Slater and Mott insulators. The Slater mechanism applies for the weak interaction region: In the presence of nested Fermi surfaces, the antiferromagnetic (AF) order appears at infinitesimal interactions based on Fermi surface nesting. On the other hand, charge fluctuations are frozen in the strong interaction regime due to the large charge gap linearly scaling with the repulsive interaction, and such a state is Mott insulating. In comparison to the current effort of exploring the SU(2) (two-component) Hubbard model in the cold atom community, we examine this problem from the perspective of an SU(6) symmetry, which applies to the ongoing experiments with ^{173}Yb. As increasing the Hubbard interaction U, there exists a transition from the antiferromagnetic state to the valence bond solid state. In contrast, in the SU(2) and SU(4) cases antiferromagnetism persists throughout the entire interaction range. In the SU(6) case, antiferromagnetism starts to develop in the weak interacting regime based on the Slater mechanism of Fermi surface nesting. As U passes a crossover value $U/t \approx 9$, the single-particle gap scales linearly with U, marking the onset of Mott physics. In the Mott regime, antiferromagnetism becomes to be suppressed as U increases, and vanishes after U passes the critical value $U_{AF,c}/t = 13.30.05$. The critical exponents are obtained via critical scalings as $\nu_{AF} = 0.60 \pm 0.02$ and $\eta_{AF} = 0.44 \pm 0.03$. As U further increases, the valence bond solid ordering appears exhibiting the anomalous dimension $\eta_{VBS} = 0.98 \pm 0.01$.

1.5 New mechanism for large gap topological states

We did pioneering works during the past decades on orbital active honeycomb systems since an early work **Phys. Rev. Lett. 99, 70401 (2007)**. This research was started with ultra-cold atom optical lattices, and has impact to the research of solid state materials as well. This work studies a class of systems which are the dual version of graphene: The point group symmetry of the honeycomb lattice constrains the onsite orbital degeneracy to be either non-degenerate, or, double-degenerate. The former corresponds to graphene based on the pz-orbital, which is orbital inactive. In contrast, the latter is orbital-active, which

In a recent work, I showed that *p*-orbital honeycomb system can provide a new mechanism to realize large gap topological systems, which is published at **Phys. Rev. B 98, 165146 (2018)**. The key idea is that both at the Γ point, and at the Dirac points K and $K^{'}$, the wavefunctions exhibit the circularly polarized orbital configurations of $p_x + ip_y$ or $p_x - ip_y$ due to spin-orbit coupling. The spin-orbit coupling strength opens the topological gaps both at the Γ and the Dirac points K and $K^{'}$-point with values equal to spin-orbit coupling strengths. As a result, the system becomes a quantum spin Hall insulator with a topological band structure. The same mechanism when applied to solid state states can be used to realize the large gap topological insulators to the order of atomic scale spin-orbit coupling. This mechanism has been realized in the bismuthene system which gives rise to the topological gap at the order of 0.8eV observed in the tunneling experimental spectroscopy.

1.6 Itinerant Ferromagnetism

Itinerant ferromagnetism (FM), i.e., FM of mobile electrons with Fermi surfaces, remains a hardcore problem of strong correlation physics. In particular, the Curie-Weiss metal phase is a long-standing problem exhibiting a dichotomic nature: The spin channel is local moment-like and incoherent while the charge channel remains coherent showing the existence of Fermi surfaces. We have made a significant progress in non-perturbatively studying itinerant FM and the Curie-Weiss metal state published at **Phys. Rev. X 5, 021032, (2015)**. Furthermore, our models are sign-problem-for

QMC simulations at all densities, which is a rare case for fermion simulations. We performed QMC simulations on the magnetic phase diagram and the Curie-Weiss metal state. Although no local magnetic moments exist as a priori, the spin channel remains incoherent showing the Curie-Weiss-type spin magnetic susceptibility down to very low temperatures at which the charge channel is already coherent, exhibiting weakly temperature-dependent compressibility. The critical scalings of magnetic phase transitions were performed based on which Curie temperatures were obtained with high numeric precision.

1.7 Many-body physics with dipolar fermions

The rapid experimental progress of ultra-cold dipolar fermions opens up a whole new opportunity to investigate novel many-body physics of fermions. We published an invited review article summarizing our series of work on dipolar fermions including both the electric and magnetic ones at **J. Phys.: Condens. Matter 26, 493203 (2014)**. Our research foci are from the perspective of unconventional symmetry due to the anisotropic electric dipolar interaction and the spin-orbit coupled magnetic dipolar interaction. These symmetry properties affect the Fermi liquid properties and Cooper pairing symmetries, leading to spin-orbit coupled collective modes and novel pairing mechanism in p-wave spin triplet channel. In electric dipolar systems, the competition between pairing instabilities in the singlet and triplet channels gives rise to a novel time-reversal symmetry breaking superfluid state. In magnetic dipolar systems, we discovered a novel pairing symmetry in the p-wave spin triplet channel with total angular momentum one, which was not studied in solid state systems before.

2 Publication list under the support from AFOSR-FA9550-14-1-0168 (09/2014-03/2020)

1. Yi Li, Congjun Wu. Unconventional symmetries of Fermi liquid and Cooper pairing properties with electric and magnetic dipolar fermions, Journal of Physics: Condensed Matter 26, 493203 (2014).

2. Zhichao Zhou, Zi Cai, Congjun Wu, Yu Wang. Quantum Monte Carlo simulation of thermodynamic properties of SU(2N) ultracold fermions in optical lattices, Physical Review B, 90, 35139 (2014).

3. Shenglong Xu, Yi Li, Congjun Wu, ”Thermodynamic properties of a 2D itinerant ferromagnet - a sign-problem free quantum Monte Carlo study, Phys. Rev. X 5, 021032, (2015).

4. Xiang-Fa Zhou, Zheng-Wei Zhou, Congjun Wu, Guang-Can Guo. The in-plane gradient magnetic field induced vortex lattices in spin-orbit coupled Bose-Einstein condensations, Physical Review A 91, 033603, (2015).

5. Da Wang, Shenglong Xu, Yu Wang, Congjun Wu. Detect edge degeneracy in interacting topological insulators using entanglement entropy, Physical Review B 91, 15118, (2015).

6. Wang Yang, Yi Li, Congjun Wu, Topological septet pairing with spin-3/2 fermions C high partial-wave channel counterpart of the 3He-B phase, Phys. Rev. Lett. 117, 075301(2016).

7. Zhichao Zhou, DaWang, Zi Yang Meng, YuWang, CongjunWu, Mott insulating states and quantum phase transitions of correlated SU(2N) Dirac fermions, Phys. Rev. B 93, 245157 (2016).

8. Jhih-Shih You, I-Kang Liu, Daw-Wei Wang, Shih-Chuan Gou, Congjun Wu, Unconventional Bose-Einstein Condensations of Two-species Bosons in the p-orbital Bands in Optical lattice, Phys. Rev. A 93, 053623 (2016).

9. Yi Li, Xiangfa Zhou, Congjun Wu, Three-dimensional quaternionic condensations, Hopf invariants, and skyrmion lattices with synthetic spin-orbit coupling, Phys. Rev. A 93, 033628 (2016).

10. Zhong-chao Wei, Congjun Wu , Yi Li, Shi-Wei Zhang, Tao Xiang Majorana Positivity and the Fermion sign problem of Quantum Monte Carlo Simulations, Phys. Rev. Lett. 116, 250601 (2016) .

11. Zhe Wang, Jianda Wu,Shenglong Xu, Wang Yang, Congjun Wu, Anup Kumar Bera, A. T. M. Nazmul Islam,Bella Lake, Dmytro Kamenskyi, Papori Gogoi, Hans Engelkamp, Nanlin Wang, Joachim Deisenhofer, and Alois Loidl, From confined spinons to emergent fermions: Observation of elementary magnetic excitations in a transverse-field Ising chain, Physical Review B 94, 125130 (2016).

12. Wei-Cheng Lee, Congjun Wu, Microscopic Theory of the Thermodynamic Properties of S-r3Ru2O7, Chin. Phys. Lett. 33, 037201 (2016).

13. Zhichao Zhou, Da Wang, Congjun Wu, and Yu Wang, Finite-temperature valence-bondsolid transitions and thermodynamic properties of interacting SU(2N) Dirac fermions, Physical Review B 95, 085128 (2017).

14. Jianda Wu, Fei Zhou, and Congjun Wu, Quantum criticality of bosonic systems with the Lifshitz dispersion, Phys. Rev. B 96, 085140 (2017).

15. Shenglong Xu, Congjun Wu, Space-time crystal and space-time group, Phys. Rev. Lett. 120, 096401 (2018).

16. Xiang-Fa Zhou, Congjun Wu, Guang-Can Guo, Ruquan Wang, Han Pu, Zheng-Wei Zhou, Synthetic Landau levels and spinor vortex matter on Haldane spherical surface with magnetic monopole, Phys. Rev. Lett. 120, 130402 (2018).

17. Zhe Wang, Jianda Wu, Wang Yang, Anup Kumar Bera, Dmytro Kamenskyi, A.T.M.Nazmul Islam, Shenglong Xu, Joseph Matthew Law, Bella Lake, Congjun Wu, Alois Loidl, Experimental Observation of Bethe Strings, Nature 554, 219 (2018)

18. Chao Xu, Jianda Wu, Congjun Wu, ”A Quantized Inter-level Character in Quantum System-s”, Phys. Rev. A 97, 032124 (2018)

19. Zhichao Zhou, Congjun Wu, Yu Wang ”Mott transition in the square-lattice SU(4) fermionic Hubbard model with a p-flux gauge field”, Phys. Rev. B 97, 195122 (2018).

20. Gang Li, Werner Hanke, Ewelina M. Hankiewicz, Felix Reis, Joerg Schaefer, Ralph Claessen, Congjun Wu, Ronny Thomale, *“Theoretical paradigm for the quantum spin Hall effect at high temperatures”*, Phys. Rev. B 98, 165146 (2018)

21. Da Wang, Lei Wang Congjun Wu, ”Slater and Mott insulating states in the SU(6) Hubbard model”, Phys. Rev. B 100, 115155 (2019) .

22. Lun-hui Hu Congjun Wu, ”Two-band model for magnetism and superconductivity in nickelates”, Phys. Rev. Research 1, 032046(R) (2019)

23. Lun-hui Hu, P. D. Johnson, Congjun Wu, ”Pairing symmetry and topological surface state in iron-chalcogenide superconductors”, Phys. Rev. Research 2, 022021(R) (2020).

3 Education and Human resource development

Projects from this proposal provide excellent theoretical training to students and postdoctoral researchers on various theoretical and numerical skills. These include band structure calculations, self-consistent mean-field theory, field theoretical methods, symmetry and topological analysis, and quantum Monte-Carlo simulations. My group members also receive training on analyzing deep physics behind the experimental phenomena.

1. Under the support from AFOSR, my group graduated two students with their Ph. D. degrees: Shenglong Xu 2017 and Wang Yang 2018. Both are very successful in academic careers in their age group. Shenglong Xu is currently a Research Assistant Professor at Texas A&M University, and Wang Yang is a postdoctoral researcher at University of British Columbia. I also provided support to the graduate student researcher Chao Xu to work on projects related to this award.

2. Under the support from AFOSR, two postdoctoral researchers worked under my guidance, Jianda Wu (from Sept. 2014-Aug. 2017), and Lunhui Hu (Sept. 2018 – March 2020). Both are very successful in academic careers in their age group. Jianda Wu is currently an Associate Professor at T. D. Lee Institute, and Lunhui Hu is current a postdoctoral researcher at Penn. State University. I also provided partial support to a postdoctoral researcher Wenbo Fu to work on projects related to this award.

3. I hold regular group meetings, which are open to both my group members and other students in the department. I educate them the general background on the research frontier of condensed matter and cold atom physics, and organize them to form study groups for classic papers. These activities have reached a satisfactory effect.

4. I support my graduate students and postdoctoral researchers to attend the APS march meeting to present our research results supported by this AFOSR award.

4 Presentation activities

Physics colloquium:

1. Department of Physics,Tulan University, Physics Colloquia, Exact results on itinerant ferromagnetism, Oct 22, 2014.

2. Department of Physics, University of Texas at Dallas, Physics Colloquia, Unconventional orbital phases with cold atoms, Sept, 2015.

3. Department of Physics, Huazhong University of Science and Technology, China, New progress on itinerant ferromagnetism and Curie-Weiss metal state, 06/24/2016.

4. Center for Nonlinear Studies, Los Alamos National Lab, Condensed Matter Science Colloquium, "Novel orbital phases in optical lattices C unconventional BEC and itinerant ferromagnetism", Dec. 14, 2016.

5. Department of Physics, Simon Fraser University, Novel orbital physics - Unconventional BEC and Curie-Weiss Metal states in optical lattices, Nov. 17, 2017.

6. Department of Physics, University of British Columbia, Novel orbital physics - Unconventional BEC and Curie-Weiss Metal states in optical lattices, Nov. 16, 2017.

7. Department of Physics, University of California, San Diego, Novel orbital physics - Unconventional BEC and Curie-Weiss Metal states in optical lattices, Nov. 9, 2017.

8. Department of Physics, University of California, San Diego, *"Symmetry and Correlation Aspect of Quantum Dynamics"*, April 18, 2019.

Physics Seminar:

1. Department of physics, MIT, Topological and strong correlation physics in the px/py orbital bands in the honeycomb lattice from solid states to optical lattices", Nov 19, 2014.

2. Department of Physics, Penn. State University, Topological and strong correlation physics in the px/py-orbital bands in the honeycomb lattice from solid states to optical lattices, Nov. 4,2014.

3. Department of Physics, Boston College, Novel Sp(2N) and SU(2N) quantum magnetism and Mott physics large spin is different, Oct. 15, 2014.

4. Department of Physics, University of British Columbia, Novel Sp(2N)/SU(2N) quantum magnetism and Mott physics - large spins are different, Nov 16, 2015.

5. Department of Physics, Purdue University, Unconventional orbital phases with cold atoms, March 3, 2016.

6. Department of Physics, Shanghai Jiaotong University, China, Interacting effects in topological systems: helical Luttinger liquid and Majorana flat-bands, July 2016.

7. Department of Physics, Johns Hopkins University, Unconventional magnetism and spontaneous spin-orbit ordering, March 29, 2017.

8. Condensed Matter Theory Center, University of Maryland, Orbital phases in optical lattices and solids: unconventional BEC and large gap topological states, March 28, 2017.

9. Department of Physics,University of California, San Diego, Unconventional magnetism and spontaneous spin-orbit ordering, Jan 18, 2017.

10. Westlake University, Hangzhou, China, "*Quantum Dynamics – Space-time group and Bethe String states"*, Nov. 23, 2018.

11. Department of Physics, **University of Buffalo**, SUNY, "*Quantum Dynamics – Space-time group and Bethe String states"*, Sept 18, 2018.

12. **Institute of Physics**, Chinese Academy of Sciences, "*Topological superconductivity with spin-$\frac{3}{2}$ half-Heusler semi-metal beyond triplet pairing"*, Sept. 7, 2018.

13. Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Quantum Dynamics - Space-time group and Bethe String states, Sept. 7, 2018.

14. Chern Institute of Mathematics, Nanka University, Quantum Dynamics - Space-time group and Bethe String states, Aug 12, 2018.

15. Center for Advanced Studies, Tsinghua University, Quantum Dynamics - Space-time crystal and Bethe String states, Aug 9, 2018.

16. Center for Quantum Materials, Peking University, Quantum Dynamics - Space-time Crystal and Bethe String States, Aug 2,2018.

17. Department of Physics, **University of Chicago**, *"Symmetry and Correlation Aspect of Quantum Dynamics"*, May 28, 2019.

18. Department of Physics, **University of California, Berkeley**, "*Orbital-active Honeycomb Materials"*, April 30, 2019.

Invited Conference talks:

1. The Topology and Mathematical Physics conference, Quaternion analyticity and 3D SU(2)Landau levels, Center of Mathematical Sciences and Applications, Harvard University, Sept 17, 2014.

2. Workshop on cold atoms at Princeton Center for Theoretical Science, Topological and strong correlation physics in the px/py orbital bands in the honeycomb lattice from solid states to optical lattices, April, 2015.

3. Institute of theoretical atomic, molecular and optical physics, Harvard, "Topological and strong correlation physics in the px/py orbital bands in the honeycomb lattice from solid states to optical lattices", Nov 21, 2014.24.

4. The 2nd Condensed Matter Conference of China, Symposium of Many-body physics, Nanjing 2016, Quantum spin dynamics of the spin-1 2 XXZ model, July 2016.

5. International Summer School for Computational Approaches for Many-body System, Sign-problem free quantum Monte-Carlo simulations on itinerant ferromagnetism in multi-orbital band systems, Beijing, Aug. 2016.

6. The 2nd Condensed Matter Conference, Chinese Physics Society, the symposium on many-body physics, Quantum dynamics of the XXZ spin chain in a longitudinal magnetic field, Nanjing, July 2016.

7. Sign 2017, International workshop in the sign problem in QCD and beyond, Fermion positivity and sign problem, University of Washington, Seattle, March, 2017.12.

8. 12th International Conference on Materials and Mechanisms of Superconductivity and High Temperature Superconductors, Spin-3/2 topological superconductivity beyond triplet pairing, Beijing, Aug 19-24, 2018, invited talk.

9. AFOSR Program Review, Quantum dynamics: Spact-time Crystal and Bethe String states, Arlington, Jun 18-22.

10. 2018 International Conference on Emergent Phenomena in Quantum Materials, Progress on Itinerant Electrons: Cruie-Weiss metal and Spin-orbit ordering, New York University in Shanghai, May 30 - Jun 1.

11. Quantum material workshop, Fudan University, Quantum dynamics: Spact-time Crystal and Bethe String states, Shanghai, April 20 -22, 2018.

12. **Workshop for Topological Quantum Information** at Shanghai Tech University, ”Orbital-active honeycomb material”, Shanghai, Nov 19-20, invited talk, 2018.

13. **Emergent phenomena in ultracold atoms: topology, interaction, and dynamics** at Kavli Institute for Theoretical Science, Beijing, ”Symmetry and Correlation Aspect of Quantum Dynamics”, June 13 2019, invited talk.

14. **Memorial workshop for Shoucheng Zhang** at Tsinghua University, ”Quarternionic analyticity and high dimensional topological matter”, June 10 2019, invited talk.

15. **Memorial workshop for Shoucheng Zhang** at Stanford University, ”Application of the symmetry principle in condensed matter physics”, May 4, 2019, invited talk.