RGC Ref.: N_HKUST601/17 NSFC Ref. : 11761161003
(please insert ref. above)

The Research Grants Council of Hong Kong
NSFC/RGC Joint Research Scheme
Joint Completion Report

(Please attach a copy of the completion report submitted to the NSFC by the Mainland researcher)

Part A: The Project and Investigator(s)

1. Project Title

Realization of 2D spin-orbit coupling of fermionic ytterbium atoms in optical lattices

二維自旋軌道耦合在光晶格中的 Yb 超冷費米子實現

2. Investigator(s) and Academic Department/Units Involved

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Prof. Gyu-Boong JO	Prof. Xiong-Jun LIU
Post	Associate Professor	Professor
Unit / Department / Institution	Department of Physics/ The Hong Kong University of Science and Technology (HKUST)	International Center for Quantum Materials/ Peking University
Contact Information	gbjo@ust.hk	xiongjunliu@pku.edu.cn
Co-investigator(s) *(with title and institution)*	N/A	N/A

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted*)
Project Start date	01/01/2018		
Project Completion date	31/12/2021		
Duration *(in month)*	48		
Deadline for Submission of Completion Report	31/12/2022		

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

(1) Development of novel schemes for realizing 1D/2D spin-orbit coupling of fermionic ytterbium in Raman-dressed optical lattices
(2) Demonstration of 1D spin-orbit coupling in optical Raman lattices
(3) Demonstration of 2D spin-orbit coupling in optical Raman lattices
(4) Revelation of non-trivial topological states in ultracold fermions

5.2 Revised Objectives

Date of approval from the RGC: N/A

Reasons for the change:

1.
2.
3. ....

6. Research Outcome

A. Synthetic topological matter with spin-orbit-coupled fermions
Over the past few years, PI's group has implemented synthetic spin-orbit coupling for ultracold ytterbium fermions by using two-photon Raman transition. Two hyperfine levels that are optically isolated from other internal levels are coupled in a momentum-sensitive manner, either in bulk or optical lattices. By engineering the band structure and its topological nature, we have realized various topological band structures as follows:

- *Observation of symmetry-protected topological band with ultracold fermions* ***Science Advances*** 4, eaao4748 (2018)
- *Observation of nodal-line semimetal with ultracold fermions in an optical lattice* ***Nature Physics*** 15 911-916 (2019)

Symmetry-protected topological band for ultracold fermions We realized a new type of SPT phase with spin-orbit-coupled fermions in engineered optical lattices. The observed SPT phase is beyond the traditional understanding from the famous Altland-Zirnbauer classification theory that a 1D SPT phase necessitates particle-hole or local chiral symmetry protection.
3D nodal line semimetal for ultracold fermions Realizing and observing 3D topological matter remain to be an open challenge in cold-atom experiments because of high complexity in experiment. In our work, we realized a 3D topological semimetal with nodal lines by combining in-plane 2D SO coupling in optical lattices with1D linear SO coupling along the z direction.

B. Non-Hermitian spin-orbit-coupled fermions Both studies highlighted the remarkable capabilities to realize and explore new topological states for ultracold atoms beyond natural conditions. However, these studies were performed in the Hermitian regime where dissipation is suppressed. Recently, we generalized the notion of spin-orbit coupling into the non-Hermitian regime by introducing controlled atom loss .

- *Topological control of quantum states in non-Hermitian spin-orbit-coupled fermions* **Nature Physics** 10.1038/s41567-021-01491-x (2022)

Good understanding of such non-Hermitian SOC is of particular importance for classifying non-Hermitian topological phases, which remains elusive in condensed matter physics. This work can set the stage for exploring topological phases in the non-Hermitian regime and open up a new direction in bandgap engineering using non-Hermitian SOC in many-body physics.

C. Interacting SU(N) fermions
Interacting fermionic matter is the foundation of matter, and fermions with enlarged spin symmetry lead to qualitatively new physics. While ordinary spin- 1/2 electrons with SU(2) symmetry are the building blocks of most of this matter, large spins with enhanced SU(N) symmetry promise new quantum phenomena and provide insights into SU(2) electronic matter. Using ytterbium fermions with tunable SU(N) symmetry, the PI's group has realized 2D SU(N) Fermi liquid and measured collective excitations [**Phys. Rev. Research**. 2 012028(R) (2020)]. Recently, thermodynamic studies have been performed by analyzing density fluctuations equivalent to compressibility [**Nature Communications** 12 2011 (2021)]. With regard to the latter experiment, the PI's group experimentally tested bosonization in a multi-component 3D fermionic system for large N; the findings suggested that the boundary between bosons and fermions can be blurred in SU(N) fermions [**Physical Review** X 10 041052 (2020)].

Potential for further development of the research and the proposed course of action ***(maximum half a page)***

In the current project, the joint team of HKUST and PKU has demonstrated synthetic spin-orbit coupling in high dimensions realizing various topological matters. These developments opened the door to the experimental investigation of topological phases that are not easily accessible in solid state system. Using the optical Raman lattice system, we demonstrated how to realize symmetry-protected topological phases with spin-orbit couplings, how to generalize distinct band structure into high dimensions, and how to effectively probe non-trivial band topology in 3D. We envision that all of those developments will allow researchers to further explore various topological states on demand. One of such examples is the Weyl semimetal that was recently observed by PKU group.

Another interesting direction of future research is to explore non-Hermitian topological systems in the presence of controlled dissipation. Although a series of outstanding questions, including the notion of topological invariant, are still under debate, most of experimental setups have been limited to classical systems.
For example, spin-orbit coupling is an important feature in an isolated systems, but less is known how it responds to dissipation in a quantum system. HKUST group showed how these two mechanism compete in cold atoms systems. In the coming years, HKUST group plans to generalize this scheme into the optical lattice system , in which the band gap opened by spin-orbit coupling can be engineered by dissipation.

7. The Layman's Summary

(describe <u>in layman's language</u> the nature, significance and value of the research project, in no more than 200 words)

In this joint project, we aimed at studying synthetic topological matter made of ultracold atoms in which their motion is entangled with angular momentum of atoms. For this goal, we exploited ytterbium ultracold fermions trapped in an artificial crystal generated by laser beams. Near the absolute zero temperature, the behaviour of those atoms mimics the quantum dynamics of electron in solids. The joint team has made several breakthroughs during the project, including the realization of topological matter in high dimensions for the first time and the demonstration of dissipative topological matter with cold atoms. Theses findings reported will lead to the better understanding of synthetic topological matter both in isolated and open systems, leading to the further development of non-trivial quantum control in highly complex systems. In addition, we anticipate that our findings would put the quantum simulation with ultracold atoms to the next level.

Part C: Research Output

8. Peer-reviewed journal publication(s) arising directly from this research project

(Please attach a copy of each publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference.)

The Latest Status of Publications				Author(s) ***(bold** the authors belonging to the project teams and denote the corresponding author with an asterisk*)*	Title and Journal/ Book *(with the volume, pages and other necessary publishing details specified)*	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Year of publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*						
2022				Zejian Ren, Dong Liu, Entong Zhao, Chengdong He, Ka Kwan Pak, Jensen Li* and **Gyu-Boong Jo***	Chiral control of quantum states in non-Hermitian spin-orbit-coupled fermions, Nature Physics 10.1038/s41567-021-01491-x	2021	Yes	Yes	No
2021				Entong Zhao, Jeongwon Lee, Chengdong He, Zejian Ren, Elnur Hajiyev, Junwei Liu and **Gyu-Boong Jo***	Heurisitic machinery for thermodynamic studies of SU(*N*) fermions with neural networks, Nature Communications 12 2011 (2021)	2021	Yes	Yes	Yes
2021				Elnur Hajiyev, Ka Kwan Pak, Chengdong He, Zejian Ren, Entong Zhao and **Gyu-Boong Jo***	578nm clock laser system for ytterbium quantum gas experiments, Journal of Korean Physical Society 79 930-936 (2021)	2021	Yes	Yes	Yes

2021				Ziting Chen, Bojeong Seo, Mingchen Huang, Mithilesh K Parit, Peng Chen***** and **Gyu-Boong Jo***	Active control of a diode laser with injection locking using a laser line filter, Review of Scientific Instruments 92 123005 (2021)	2021	Yes	Yes	No
2020				Bo Song, Yangqian Yan, Chengdong He, Zejian Ren**,** Qi Zhou* and **Gyu-Boong Jo***	Evidence for bosonization in a three-dimensional gas of SU(*N*) Fermions, Physical Review X 10 041052 (2020)	2021	Yes	Yes	Yes
2020				Bojeong Seo, Peng Chen*****, Ziting Chen, Weijun Yuan, Mingchen Huang, Shengwang Du **and Gyu-Boong Jo***	Efficient production of a narrow-line erbium magneto-optical trap with two-stage slowing, Physical Review A 102 013319 (2020)	2021	Yes	Yes	Yes
2020				Bo Song*****, Chengdong He, Zejian Ren, Entong Zhao, Jeongwon Lee, and **Gyu-Boong Jo***	Effective Statistical fringe removal algorithm for high-sensitivity imaging of ultracold atoms, Physical Review Applied 14 034006 (2020)	2021	Yes	Yes	Yes

2019				Bo Song, Chengdong He, Sen Niu, Long Zhang, Zejian Ren, Xiong-Jun Liu* and **Gyu-Boong Jo***	Observation of nodal-line semimetal with ultracold fermions in an optical lattice, Nature Physics 15 9 11-916 (2019)	2019	Yes	Yes	Yes
2019				Chengdong He, Elnur Hajiyev, Zejian Ren, Bo Song and **Gyu-Boong Jo***	Recent Progresses of ultracold two-electron atoms, Journal of Physics B: Atomic, Molecular and Optical Physics 102 001 52 (2019)	2019	Yes	Yes	Yes

9. Recognized international conference(s) in which paper(s) related to this research project was/were delivered *(Please attach a copy of each delivered paper. All listed papers must acknowledge RGC's funding support by quoting the specific grant reference.)*

Month/Year/ Place	Title	Conference Name	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
6/2021/Dallas	Efficient creation of dipolar ^{168}Er Bose-Einstein condensates for quantum simulation	51th APS DAMOP meeting	2021	Yes	Yes	Yes
6/2021/Dallas	Non-Hermitian spin-orbit coupled quantum gases	51th APS DAMOP meeting	2021	Yes	Yes	Yes

6/2021/Dallas	Applying machine learning techniques to ultracold quantum gases	51th APS DAMOP meeting	2021	Yes	Yes	Yes
6/2021/Dallas	Density fluctuations in a two-dimensional SU(N) Fermi gas	51th APS DAMOP meeting	2021	Yes	Yes	Yes
6/2020/Virtual	Machine learning aided study of a three-dimensional gas of SU(*N*) fermions	51th APS DAMOP meeting	2020	Yes	Yes	Yes
6/2020/Virtual	Dynamical control and detection of topological properties in 2D optical lattices	51th APS DAMOP meeting	2020	Yes	Yes	Yes
6/2019/Wisconsin	Realization of three-dimensional nodal- line semimetal with ultracold fermions	50th APS DAMOP meeting	2019	Yes	Yes	Yes
6/2019/Wisconsin	Measurement of Tan’s contact in SU(*N*) fermions	50th APS DAMOP meeting	2019	Yes	Yes	Yes
6/2019/Wisconsin	Interactions and collective excitations in a SU(*N*) Fermi gas	50th APS DAMOP meeting	2019	Yes	Yes	Yes
6/2019/Wisconsin	Exploring 3D topological matter with spin-orbit-coupled fermions in optical lattices	50th APS DAMOP meeting	2019	Yes	Yes	Yes

7/2018/Barcelona	Observation of semimetal phase for ultracold fermions with 2D spin-orbit coupling in an optical lattice	International Conference on Atomic Physics (ICAP)	2019	Yes	Yes	Yes
8/2018/Hong Kong	Synthetic spin-orbit coupling for ultracold fermions in optical lattices	CLEO pacific RIM	2019	Yes	Yes	Yes

10. Student(s) trained *(Please attach a copy of the title page of the thesis.)*

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
Bo Song	PhD	2014-09-01	2019-04-25
Chengdong He	PhD	2015-09-01	2021-08-10
Zejian Ren	PhD	2016-09-01	2021-08-17
Elnur Hajiyev	PhD	2015-09-01	2021-08-30
Entong Zhao	PhD	2018-09-01	2023-09-30 (expected)

11. Other impact *(e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, etc.)*

Media coverage

(1) “Researchers find new way of gaining quantum control from loss“
Highlighted in Phys.org, Sciemag, MirageNews,AzoQuantum, ScienceDaily, 163.com, qianzhan.com, HKUST news and EurekAlert (2022)

(2) “Physicists Quantum Simulate a System in which Fermions with Multiple Flavors Behave Like Bosons”
Highlighted in Phys.org, Bioengineer.org, Genius Science, HKUST news and EurekAlert (2020)

(3) "Scientists unveil first quantum simulation of 3-D topological matter with ultracold atoms"
Highlighted in Phys.org, EureaAlert, ScienceDaily nanowerk photonicsonline
News articles in HKUST news, PKU news, Croucher Foundation (2019)

(4) "Physicists quantum simulate topological materials with ultracold atoms"
Highlighted in Phys.org, EurekAlert, ScienceDaily, ScienceNewsLine, Sina, PKUnew (2018)

Awards by the PI
1. RGC Research Fellow (2021)
2. UROP Faculty Research Award, HKUST (2021)
3. Named Professorship, HKUST (2021)

4. School Research Award, School of Science, HKUST (2019)

Awards by group members

1. Ting Hin Mak, Mr.Armin and Mrs.Lillian Kitchell UROP Awardm, HKUST (2021)
2. Weijun Yuan, Academic Achievement Medal, HKUST (2020)
3. Chengdong He, School of Science Postgraduate Research Excellence Award (2019)
4. Mingchen Huang, Huawei PhD fellowship (Sep. 2019)
5. Dr. Jeongwon Lee,selected as a IAS junior fellow, HKUST (Feb. 2019)
6. Bo Song, 2017/18 School of Science Excellence Research Awards (May 2018)

12. Statistics on Research Outputs *(Please ensure the summary statistics below are consistent with the information presented in other parts of this report.)*

	Peer-reviewed journal publications	Conference papers	Scholarly books, monographs and chapters	Patents awarded	Other research outputs (Please specify)
No. of outputs arising directly from this research project [or conference]	9	12	0	0	0