CRF 8G (Revised Sep 15)

RGC Reference	HKU8/CRF/11G
please insert ref. above	

The Research Grants Council of Hong Kong
Collaborative Research Fund Group Research Projects
Completion Report

(*for completed projects only*)

Part A: The Project and Investigator(s)

1. Project Title

Quantum Control and Quantum Information Processing

2. Investigator(s) and Academic Department/Units Involved *(please highlight approved changes in the composition of the project team and quote the date when RGC granted approval of such changes)*

Research Team	Name/Post	Unit/Department/Institution	Average number of hours per week spent on this project in the current reporting period
Project Coordinator	Z. D. Wang/ Chair Professor	Department of Physics / HKU	12
Co-Principal investigator(s)	H. F. Chau/ Professor	Department of Physics / HKU	10
	S. Du/Associate Professor	Department of Physics / HKUST	10
	R.B. Liu / Associate Professor	Department of Physics / CUHK	10
	W. Yao / Assoc. Prof.	Department of Physics / HKU	10

3. Project Duration

	Original	Revised	Date of RGC Approval *(must be quoted*)
Project Start Date	01.06.2012		
Project Completion Date	31.05.2015		
Duration (*in month*)	36		
Deadline for Submission of Completion Report	31.05.2016		

Part B: The Final Report

5. Project Objectives

5.1 Objectives as per original application

1. To explore exotic topological superfluidity of Dirac fermions and quantum particles with effective spin-orbit interactions both analytically and numerically, and address its promising or potential applications in robust quantum information processing. By using the cold-atoms plus well-designed laser beams, we will simulate and manipulate various novel quantum phenomena that are fundamentally important but can hardly be observed in natural materials.
2. To investigate the preparation of quantum state with multi-partite entanglement by irreversible dynamics in realistic physical systems; explore the use of these quantum states in applications such as quantum communication and quantum metrology.
3. To study dynamical decoupling and control for protecting quantum coherence in novel matters and devices such as topological insulators/superconductors and cold atoms in optical fields, so as to suppress the environmental noises.
4. To establish a theory on detection of new physics in topological matters via coherence of central spins, by developing the concepts of electron spin resonance spectroscopy.
5. To develop a linear quantum information processor using narrowband single photons with time qubits.
6. To investigate the security of quantum key distribution in realistic experimental setups including those using narrowband photon pairs.

5.2 Revised objectives

1. To study quantum state control and applications using photons, atoms, and artificial atoms in solids, including to explore fundamental quantum physics with applications in quantum information processing and to develop novel experimentally feasible approaches/setup for quantum control and quantum metrology as well as for quantum simulation.
2. To explore realistic quantum communication based on photons and atoms by concentrating on experimental schemes and implementation, which includes to develop and to implement secured quantum key distribution protocols using entangled single photons with long coherence time.

Date of approval from the RGC: 24-02-2012

Reasons for the change:

Since the awarded amount of grant is significantly reduced as compared with the originally requested one, which has an obvious impact on our original plan, we, following the CRF Sub-Committee's advice and taking into account reviewers' relevant comments, recast the original objectives (1-4) and (5-6) respectively as the present revised objectives (1) and (2), focusing on the collaborative work of the experimental part as well as the relevant theoretical research.

6. Research Outcome

6.1 Major findings and research outcome
(maximum 1 page; please make reference to Part C where necessary)

(1) We designed and experimentally demonstrated a noise-resilient two-qubit gates via in diamond [**Nat. Comm. 4**, 2254 (2013)], and experimentally demonstrated detection of NMR and structural characterization of a single pair of nuclear spin qubits under multipulse dynamical decoupling control [**Nat. Phys. 10**, 21 (2014)]. In addition, we proposed a scheme to detect quantum phase transitions at high temperatures using the qubit decoherence [**Phys. Rev. Lett. 109**, 195701 (2012)]. Moreover, we established a unified theory of topological gapless bands including topological metals and nodal superconductors, and addressed its applications and relevant models [**Phys. Rev. Lett. 110**, 240404(2013); **Phys. Rev. Lett. 114**, 206602 (2015); **Phys. Rev. Lett. 116**, 016401 (2016)]. We also discovered novel quantum control possibilities of excitons in monolayer transition metal

dichalcogenides [**Nat. Comm. 5**, 3876 (2014)], and addressed pseudospins in these layered dichalcogenides [**Nat. Phys. 10**, 343 (2014)].

(2) We reported the first experimental demonstration of single-photon-based differential-phase-shift (DPS) quantum key distribution (QKD), which meets the unconditional security requirement [**Opt. Express 21**, 9505]. We demonstrated an efficient experimental scheme for generating subnatural linewidth polarization-entangled photon pairs with controllable temporal length. [**Phys. Rev. Lett. 112**, 243602 (2014)]. In addition, we proposed an experimentally feasible highly error-tolerant quantum key distribution scheme using qudits [**Phys. Rev. A 92**, 062324 (2015)], which is going to be implemented in some experimental groups.

In summary, we have published 2 papers in Nature Physics, 2 in Nature Communications, 6 in Physical Review Letters, 2 in Optical Express, 16 in Physical Reviews, and 4 in other journals.

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

Our unified theory of topological gapless bands and the proposed models pave the way for exploring novel topological matter. Several experimental groups have been working along the lines suggested by us. In addition, our quantum key distribution scheme using qudits is going to be implemented in some experimental groups in the mainland of China.

6.3 Research collaboration achieved *(please give details on the achievement and its relevant impact)*

During the period of this CRF project, the PC and 4 Co-Is as well as the group members had a number of meetings/workshops and round-table discussions. In particular, Du's group at HKUST and Chau's group at HKU had a half-day meeting plus intensive later discussions, and worked together to have realized the first experimental demonstration of single-photon-based DPS type of QKD, which was published in Optics Express. In addition, the PC, RBL, and WY as well as some of their group members had meetings/discussions, plus the inter-institutional ones among the PC's group and RBL's group. The work on the boundary-bulk correspondence of topological systems of the PC's group, and the work of Yao's group on the valley orbit coupling of excitons in monolayer transition metal dichalcogenides benefited from these meetings/discussions, which were acknowledged in the publications. In addition, the PC and Du's group had also meetings and discussions, and the work on single-photon transport of PC acknowledged the discussions.The PC's group at HKU and Dr. M. Gong in Liu's group at CUHK collaborated on study and simulation of some exotic topological systems, and the work was published.

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)

Quantum control and quantum information processing using atomic optical systems and solid state systems are cutting edge sciences with applications in device science, communication, cryptography, and metrology. In this collaborative project, we have brought together the existing research strength in these areas in Hong Kong to form a team to make the following important research achievements. (1) We realized the detection of single nuclear spin pairs, which may help advance single-molecule nuclear magnetic resonance spectroscopy. (2) We realized experimentally a quantum communication protocol that meets the unconditional security requirement. (3) We established a unified theory of topological metals, which are novel matter to rarely exist in nature. All of these results have been published in leading journals including Nature Physics, Physical Review Letters, and Nature Communications *etc.*, which will not only advance our understanding of the exotic quantum science, but also expand our imagination for tomorrow's quantum technology innovation.

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Part C: Research Output

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

(Please attach a copy of the 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) *(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 RGC *(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)						
2013				S.L. Zhu*, Z.D. Wang*, Y.H. Chan, L.M. Duan	Topological Bose-Mott Insulators in a One-Dimensional Optical Superlattice / Physical Review Letters 110, 075303	2013	No	Yes	Yes
2013				T. Zhou, Z. D. Wang*	Revealing Majorana fermion states in a superfluid of cold atoms subject to a harmonic potential /Phys. Rev. B 88, 155114	2013	No	Yes	Yes
2013				Y. X. Zhao, Z. D. Wang*	Topological Classification and Stability of Fermi Surfaces / Physical Review Letters 110, 240404	2013	No	Yes	Yes
2013				Wei Chen, R. Shen,* Z. D. Wang*, L. Sheng, B. G. Wang, D. Y. Xing	Quantitatively probing two-electron entanglement with a spintronic quantum eraser, Phys. Rev B 87,155308	2013	No	Yes	Yes

2013				Chang Liu, Shanchao Zhang, Luwei Zhao, Peng Chen, C. -H. F. Fung, H. F. Chau, M. M. T. Loy, and Shengwang Du*	"Differential-phase-shift quantum key distribution using heralded narrow-band single photons," Opt. Express 21, 9505	2013	No	Yes	Yes
2013				Wenhao Guo, Shuigang Xu, Zefei Wu, Ning Wang, M. M. T. Loy, and Shengwang Du*	"Oxygen-assisted charge transfer between ZnO quantum dots and graphene," Small 9, 3031	2013	No	Yes	Yes
2013				Daniel M. Farkas, Kai M. Hudek, Shengwang Du, and Dana Z. Anderson*	"Efficient direct evaporative cooling in an atom chip magnetic trap," Phys. Rev. A 87, 053417	2013	No	Yes	Yes
2014				Fazhan Shi, Xi Kong, PengfeiWan, Fei Kong, Nan Zhao, Ren-Bao Liu and Jiangfeng Du*	Sensing and atomic-scale structure analysis of single nuclear-spin clusters in diamond/ Nature Physics 10, 21	2013	No	Yes	Yes
2013				Gang-Qin Liu, Hoi Chun Po, Jiangfeng Du, Ren-Bao Liu*, Xin-Yu Pan*	Noise-resilient quantum evolution steered by dynamical decoupling / Nature Communications 4, 2254	2013	No	Yes	Yes
2013				Shao-Wen Chen, Zhan-Feng Jiang & Ren-Bao Liu*	Quantum criticality at high temperature revealed by spin echo / New Journal of Physics 15 043032	2013	No	Yes	Yes

2012				Bo-Bo Wei & Ren-Bao Liu*	Lee-Yang Zeros and Critical Times in Decoherence of a Probe Spin Coupled to a Bath / Physical Review Letters 109, 185701	2013	No	Yes	Yes
2013				Zhirui Gong, and Wang Yao	Protecting dissipative quantum state preparation via dynamical decoupling, Phys. Rev. A 87, 032314	2013	No	Yes	Yes
2013				Hongyi Yu, and Wang Yao*	Entanglement detection and quantum metrology by Raman photon-diffraction imaging, Phys. Rev. A 87, 042303	2013	No	Yes	Yes
2013				Zhao-Ming Wang, Lian-Ao Wu*, Michele Modugno, Wang Yao, and Bin Shao	Fault-tolerant almost exact state transmission, Sci. Rep. 3, 3128	2013	No	Yes	Yes
2014				Y. X. Zhao, Z. D. Wang*	Topological connection between stability of Fermi surfaces and topological insulators & superconductors, Phys. Rev. B89, 075111		Yes	Yes	Yes
2013				W. Jia, Z. D. Wang*	Single-photon transport in a one-dimentional waveguide coupling to a hybrid atom-optomechanical system, Phys.		Yes	Yes	Yes

					Rev. A88, 063821				
2013				H. F. Chau	Quantum speed limit with forbidden speed intervals, Phys. Rev. A87, 052141		Yes	Yes	Yes
2014				Hongyi Yu, Guibin Liu, Pu Gong, Xiaodong Xu and Wang Yao*	Dirac cones to Dirac saddle point of bright excitons in monolayer transition metal dichalcogenides, Nat. Commun. 5, 3876		Yes	Yes	Yes
2014				X. Xu*, Wang Yao*, D. Xiao, and T. F. Heinz,	Spin and pseudospins in layered transition metal dichalcogenides, Nature Physics 10, 343 (2014).		Yes	Yes	Yes
2014				Y. X. Zhao and Z. D. Wang*	Exotic topological types of Majorana zero-modes and their quantum manipulation, Phys. Rev. B 90, 115158		Yes	Yes	Yes
2014				Kaiyu Liao, Hui Yan*, Junyu He, Shengwang Du, Zhi-Ming Zhang, Shi-Liang Zhu*	"Subnatural-linewidth polarization-entangled photon pairs with controllable temporal length," Phys. Rev. Lett. 112, 243602 (2014).		Yes	Yes	Yes

2014				Peng Chen, Weihua Wang, Nian Lin, and Shengwang Du*	"Manipulating photon emission efficiency with local electronic states in a tunneling gap," Opt. Express 22, 8234 (2014).		Yes	Yes	Yes
2015				Y. X. Zhao and Z. D. Wang*	Disordered Weyl semimetals and their topological family, Phys. Rev. Lett. 114, 206602		Yes	Yes	Yes
2015				T. Mao and Z. D. Wang*	Quantum Simulation of Topological Majorana Bound States and Their Universal Quantum Operations Using Charge-Qubit Arrays, Phys. Rev. A 91, 012336		Yes	Yes	Yes
2015				T. Zhou*, X.-J. Li, Y. Gao, and Z. D. Wang*	Charged-impurity-induced Majorana fermions in topological superconductors, Phys. Rev. B 91, 014512		Yes	Yes	Yes
2015				D. W. Zhang*, S.-L. Zhu, and Z. D. Wang*	Simulating and exploring Weyl semimetal physics with cold atoms in a two-dimensional optical lattice, Phys. Rev. A 92, 013632		Yes	Yes	Yes
2015				Y. X. Zhao and Z. D. Wang*	General response theory of topologically stable Fermi points and its implications for		Yes	Yes	Yes

					disordered cases, Phys. Rev. B 92, 085143				
2015				Z. Y. Xue*, M. Gong, J. Liu, Y. Hu, S. L. Zhu, and Z. D. Wang*	Robust interface between flying and topological qubits, Sci. Rep. 5, 12233		Yes	Yes	Yes
2015				H. F. Chau	Quantum key distribution using qudits that each encode one bit of raw key, Phys. Rev. A 92, 062324		Yes	Yes	Yes
2016				Y. X. Zhao and Z. D. Wang*	Novel Z_2 topological metals and semimetals, Phys. Rev. Lett. 116, 016401		Yes	Yes	Yes
2016				T. Zhou*, Y. Gao, and Z. D. Wang*	Superconductivity in doped inversion-symmetric Weyl semimetals, Phys. Rev. B 93, 094517		Yes	Yes	Yes
2016				J. P. Lv and Z. D. Wang*	Exotic Haldane superfluid phase of soft-core bosons in optical lattices, Phys. Rev. B 93, 174507		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 conference abstract)*

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 RGC *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Aug/2012/ Dunhuang	Quantifying Two-electron Entanglement with a Spintronic Quantum Eraser (Invited talk),	The International Conference on Quantum Foundation and Technology	2013	No	Yes	Yes

May/2013/ Nanjing	Topological Stability of Fermi Surfaces and Its Connection to Topological Insulators and Superconductors (Invited talk)	14th International Workshop on Vortex Matter in Superconductors	2013	No	Yes	Yes
June/2013/Shanghai	Searching for New Topological Types of Majorana Fermions (Invited talk)	International Workshop on Frontiers in Quantum Information Science	2013	No	Yes	Yes
March/2013/ Baltimore, Maryland, USA	Strain-induced piezoelectric field effects on the optical properties of ZnO nanowires	American Physical Society March Meeting 2013	2013	No	Yes	Yes
June/2013/Rochester, New York, USA	Single-Photon Differential-Phase-Shift Quantum Key Distribution	The Rochester Conferences on Coherence and Quantum Optics (CQO) and the Quantum Information and Measurement (QIM) Meeting	2013	No	Yes	Yes
Oct/2013/Jeju, S. Korea	Generation and Application of Narrow-Band Photon Pairs (Invited talk)	The 4th Int'l Quantum Optics Workshop	2013	No	Yes	Yes
15-18 Dec 2013, Seoul, Korea	Dynamical decoupling for decoherence control and noise-resilient quantum gate (Invited talk)	Asia-Pacific Conference and Workshop on Quantum Information Science 2013		Yes	Yes	Yes
15-18 Dec 2013, Seoul, Korea	Revealing New Types of Majorana Fermions and Their Potential Application in Topological Quantum Computation (Invited talk)	Asia-Pacific Conference and Workshop on Quantum Information Science 2013		Yes	Yes	Yes
12-15 Dec 2014, Tainan (Taiwan)	Exploring and Simulating Topological Quantum Physics (Invited talk)	Asia-Pacific Conference and Workshop on Quantum Information Science 2014		Yes	Yes	Yes
27-29 May 2015, Chongqing	Topological metals (Invited talk)	The 4th World Conference in Advanced Materials		Yes	Yes	Yes
23-26 Aug 2015, Stockholm (Sweden)	Topological metals and semimetals (Invited talk)	The Advanced Materials of World Congress		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
Shanchao Zhang	PhD	09/2009	08/2013
Wenhao Guo	PhD	09/2009	08/2013

Chang Liu	PhD	09/2010	08/2014
Yuxin Zhao	PhD	09/2010	08/2014

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

Collaborations with others at University of Science & Technology of China, Institute of Physics (CAS), Nanjing University, South China Normal University, University of Michigan at Ann Arbor, and University of Colorado at Boulder.