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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

Theoretical and Experimental Study of Quantum Computing and Quantum Simulation with Electron and Nuclear Spins in Solids

用固體中電子及核自旋進行量子計算及量子仿真之理論與實驗研究

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	LIU, Renbao, Prof. 劉仁保教授	DU, Jiangfeng, Prof. 杜江峰教授
Post	Professor 教授	Professor 教授
Unit / Department / Institution	Department of Physics, The Chinese University of Hong Kong 香港中文大學物理系	Department of Modern Physics, University of Science & Technology of China 中國科技大學 現代物理系
Co-investigator(s) *(with title)*	LIN, Haiqing, Prof. 林海青教授	PENG, Xinhua, Prof. 彭新華教授

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted)*
Project Start date	01 Jan 2012		
Project Completion date	31 Dec 2014		
Duration *(in month)*	36 months		
Deadline for submission of Joint Completion Report	31 Dec 2015		

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. Design and demonstration of one- and two-qubit quantum gates of electron and nuclear spins in solids. The theoretical research will provide schemes for identifying and characterizing a coupled electron-nuclear spin system and design controlling schemes, including timing of pulse sequences for dynamical decoupling control and pulse shaping for non-Abelian geometrical control. The experimental research will characterize the physical systems and implement the control schemes. In this stage,

the experimental control techniques, such as pulse shaping and multi-channel pulse sequences, will be improved;

2. Design and demonstration of small quantum algorithms and simulations of quantum phase transitions using a few spin qubits in solids. The theoretical research will develop schemes to analyze a multi-spin systems such as a center electron spin coupled to several nuclear spins and therefore design control gates of the multi-qubit systems (e.g., by applying pulses flipping the center electron spin). The theoretical team will also apply the quantum information approach to many-body physics in few-qubit systems. The experimental research will demonstrate the control schemes and small quantum algorithms such as multi-qubit Deutsch-Jozsa algorithm and quantum error correction and test the quantum information approaches to quantum phase transitions and quantum simulation;

3. Design of scalable architectures of quantum computers based on solid-state spin systems. The theoretical research will design the architecture and run numerical simulations of the design. The experimental team will test the key elements of the architecture.

5.2 Revised Objectives

Date of approval from the RGC: ____________________

Reasons for the change: ____
____

1.
2.
3. ....

6. Research Outcome

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

1. We designed and implemented noise-resilient quantum gates on electron and nuclear spins in diamond using dynamical decoupling. We put forward a general scheme to design quantum gates resilient to environmental noises up to arbitrary order of precision. The scheme is based on dynamical decoupling. The designed quantum gates include Phase gates, C-NOT gates, NOT gates, etc. We experimentally demonstrated a high-fidelity (>90%) C-NOT two-qubit gate on a nitrogen-vacancy center electron spin and a 13C nuclear spin in diamond. The gate by design is demonstrated robust against decoherence (coherence time extended by more than 30-fold). Part of the result is published in *Nature Communications* [4, 2254 (2013)].
2. We developed methods to detect ^{13}C nuclear spin pairs in diamond by optically detected magnetic resonance of a nitrogen-vacancy center spin under multi-pulse dynamical decoupling control. The spatial configuration and structure of the pair are identified with atomic scale resolution, by comparing the experimental data and numerical simulations. The paper reporting this result is published in *Nature Physics* [*10, 21 (2014)*].
3. We have been carried out study of phase transitions and more generally detection of many-body physics using central spin decoherence. Currently in experiments we have conducted simulation of the many-body system using liquid-state nuclear magnetic resonance. In theory, we are studying the simulation of many-body physics using multiple spins in diamond. We observed Lee-Yang zeros (which were discovered in theory by T. D. Lee and C. N. Yang in 1952) for the first time. The results are published in *Physical Review Letters* [114, 010601 (2015)].

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

Based on the studies in this project, we find that it is promising to use dynamical decoupling to tune the strength of quantum measurement of a single nuclear spin weakly coupled to a nitrogen-vacancy center and realize the single-shot quantum measurement, which is essential to quantum computing. This, if realized experimentally, would great extend the number of nuclear spin qubits and may help achieve fault-tolerant coding. We will pursue further in experiments along this direction.

7. The Layman's Summary

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

Physical implementation of scalable quantum computers is the central topic of current research of quantum information. Quantum simulation of interacting many-body systems has been the first motivation and is still a most challenging task for research of quantum computing. Spins in solids are a most promising candidate system for quantum computing. The key issues are how to protect quantum coherence and implement high-fidelity quantum gates in complex solid-state environments and how to scale up the system and control design. This project will tackle these important problems. This project targets at physical implementation of few-qubit quantum computing and quantum simulation using electron and nuclear spins in solids. In this project, we have put forward schemes in theory and demonstrated the implementation in experiments of controlling and measuring electron and nuclear spin qubits in a fault-tolerant manner, which tolerates the decoherence. High fidelity of quantum gates has been achieved. We also realized charazterization of a cluster of nuclear spin qubits that are weakly coupled to a central electron spin qubits. This project will pave the way for scalable quantum computing in solid-state spin systems and may also rejuvenate high-precision magnetic resonance spectroscopy.

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)*						

2013				Gang-Qin Liu, Hoi Chun Po, **Jiangfeng Du, Ren-Bao Liu*,** and Xin-Yu Pan*	*Noise-resilient quantum evolution steered by dynamical decoupling*, **Nature Communications** 4:2254 (2013). DOI: 10.1038/ncomms3254	Yes 30 Jun 2013	Yes	Yes	Yes
2014				Fazhan Shi, Xi Kong, Pengfei Wang, Fei Kong, Nan Zhao, **Ren-Bao Liu, Jiangfeng Du***	*Sensing and atomic-scale structure analysis of single nuclear-spin clusters in diamond,* **Nature Physics** *10, 21 (2014) doi:10.1038/nphys2814*	No	Yes	Yes	No
2015				**Xinhua Peng***, Hui Zhou, Bo-Bo Wei, Jiangyu Cui, J**iangfeng Du*, Ren-Bao Liu***	Experimental Observation of Lee-Yang Zeros. **Physical Review Letters** 114, 010601 (2015)	No	Yes	No	No

2013				Chang S. Shin, Claudia E. Avalos, Mark C. Butler, Hai-Jing Wang, Scott J. Seltzer, **Ren-Bao Liu**, Alexander Pines, and Vikram S. Bajaj*	Suppression of electron spin decoherence of the diamond NV center by a transverse magnetic field. **Physical Review B** 88, 161412(R) (2013) (Editor's suggestion).	No	Yes	Yes	No
2014				Chang S. Shin, Mark C. Butler, Hai-Jing Wang, Claudia E. Avalos, Scott J. Seltzer, **Ren-Bao Liu**, Alexander Pines, and Vikram S. Bajaj*	Optically detected nuclear quadrupolar interaction of N14 in nitrogen-vacancy centers in diamond. **Physical Review B** 89, 205202 (2014). http://journals.aps.org/prb/abstract/10.1103/PhysRevB.89.205202	No	Yes	Yes	No

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)*
August 2014 Cambridge, UK	Preserving quantum coherence of spins in the presence of noises	2014 Workshop on Principles and Applications Of Control to Quantum Systems	No	Yes	Yes	No
Aug 2014 Brisbane, Australia	Coupling of an ensemble of spins in diamond to a cavity for solid-state superradiant maser at room temperature	2014 Workshop on Quantum Information using NV centres in Diamond (QDiamond 14)	No	Yes	Yes	No
July/2013 Chiba, Japan	Quantum Information Processing with Diamond	The 12th Asia-Pacific Physics Conference	Yes 30 Jun 2013	Yes	Yes	No
09/2013 Kyoto, Japan	Decoherence of nitrogen-vacancy center spins in diamond	JSAP-MRS Joint Symposia	No	Yes	Yes	No
08/2013 Berkshire, UK	Exploring and exploiting the quantumness of nuclear spin baths	Windsor 2013 PPCQ Workshop on Dynamics of Complex Quantum Systems	No	Yes	Yes	No
Dec 2013 Seoul, Korea	Dynamical decoupling for decoherence control and noise-resilient quantum gates	Asia-Pacific Conference and Workshop on Quantum Information Science 2013	No	Yes	Yes	No
Jul, 2013 Weihai, Shandong, China	Central Spin Decoherence: Fundamentals and Applications	The 19th National Semiconductor Physics Conference (Plenary Talk)	No	Yes	Yes	No

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
CHEN, Dongqing	PhD	Aug 2011	Jul 2015

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

We developed collaboration with Professor Xinyu Pan's group in Institute of Physics, Chinese Academy of Sciences and Professor A. Pines's group in University of California, Berkeley.

Ren-Bao Liu was awarded the Huang Kun Prize 2013 (Chinese Physical Society)