RGC Ref.: N_CUHK403/16 NSFC Ref. : 11661161018
(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

Quantum simulation of dynamical many-body physics by solid-state NMR

固態核磁共振對動態多體物理的量子模擬

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	LIU, Renbao, Professor	PENG, Xinhua, Professor
Post	Professor, Director of Centre for Quantum Coherence	Professor, Head of the Department of Modern Physics
Unit / Department / Institution	Department of Physics, The Chinese University of Hong Kong	Department of Modern Physics, University of Science and Technology of China
Contact Information	rbliu@cuhk.edu.hk +852-3943 6312	xhpeng@ustc.edu.cn +86-551-63602439
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	1 Jan 2017	N.A.	N.A.
Project Completion date	31 Dec 2020	N.A.	N.A.
Duration *(in month)*	48	N.A.	N.A.
Deadline for Submission of Completion Report	31 Dec 2021	N.A.	N.A.

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. Engineering of quantum many-body interactions for nuclear spins in solid-state systems. Dynamical decoupling will be designed and experimentally implemented to average the interactions between nuclear spins to realize effective Hamiltonians on demand. Switching between different effective Hamiltonians will be realized by changing the dynamical decoupling sequences.
2. Quantum simulation of dynamical phase transitions using solid-state NMR. We will induce quench dynamics in nuclear spins by switching the effective Hamiltonians. The dynamical evolution will be measured by quantum interferometry. Both the qualitatively different evolutions for quench into different parameter regimes and the sudden changes of evolution at critical times will be investigated.
3. Study of thermodynamics in the complex plane of parameters using solid-state NMR. We will measure the dynamical evolution of nuclear spins under quench and relate its features (such as characteristic oscillations) to Lee-Yang zeros (and other types of singularities in the complex plane) and critical phenomena in time-domain.

5.2 Revised Objectives

N.A.

Date of approval from the RGC: N.A.

Reasons for the change: N.A.

6. Research Outcome

Major findings and research outcome

(maximum 1 page; please make reference to Part C where necessary)

1. We studied the dynamical quantum phase transitions using a one-dimensional quantum spin model (XY model) under a complex magnetic field. We find that the quantum criticality occurs no only at the exception points, but also at the branch cuts where the imaginary part of excitation gap is zero, signified by the divergence of the spin-spin correlation lengths. Using the dual XY model obtained by the Wick rotation to the non-Hermitian Hamiltonian, we obtain the transformation between the ferromagnetic and paramagnetic phases. This work leads to a unified framework for the dynamical phase transitions, quantum phase transitions, and topological phase transitions. [*paper 01*]
2. We propose a scheme to measure many-body correlations in a quantum bath to arbitrary order, using weak measurement through central spin quantum sensors. We establish the general relation between the correlations in a quantum bath and the correlations of weak measurements on the quantum bath and therefore put forward a systematic method for reconstructing the bath correlations to arbitrary orders from the weak measurement correlations. This work provides a new approach to studying quantum many-body physics. [*paper 11*]
3. We have derived the reachability set of the average Hamiltonian of multi-pulse sequences in a homonuclear solid-state nuclear magnetic resonance system for the first time, and proposed a general design method for obtaining arbitrary average Hamiltonian in reachable set. A new type of homonuclear decoupling pulse sequence with controllable narrow contraction factor is designed. The comparison experiments show that the new decoupling sequence has the properties of high narrowing factor and low duty cycle. [*paper 22*]
4. We setup the experimental platform of spin noise detection with Faraday rotation spectroscopy on alkali-metal atom vapor and observed the correlation spectra of the spin noise of ^{85}Rb and ^{87}Rb measured in radio-frequency range as well as the micro-wave range (~6.8 GHz). [*paper 03*]
5. Using NMR experiments, we extracted quantum correlations of nuclear spins using quantum sensing schemes. In particular, we discovered that the quantum force applied from a quantum sensor to the nuclear spin baths can be pre- and post-selected to be either a real or an imaginary force so that the quantum nonlinear spectroscopy of the correlations of commutators or anti-commutators can be realized. We designed the schemes of measuring the high-order quantum correlations for ensemble nuclear spin sensors, which are particularly suitable for NMR experiments. We optimized the schemes to be robust against control errors. [*paper 01*]
6. By engineering the Hamiltonians, we prepared many-body correlated states in solid-state NMR systems and evaluated the metrologically useful correlation of these states by the multiple quantum coherence spectra. We further extracted their quantum Fisher information, showing it increases with increasing the number of correlated spins. [*paper in preparation*]
7. We discovered that the gauge field in a nonlinear quantum system resembles the curvature of a de Sitter space and the critical surfaces of quantum many-body systems resemble the big bang of the 2+1 de Sitter space, providing a theoretical framework for quantum simulation of cosmological models [*paper 26*]. We engineered the natural Hamiltonian of samples to simulate random spin models. We observed two different quench dynamics: the oscillation dynamics and the slow decay dynamics, which resemble two different cosmological models, namely, the black hole model and the wormhole model. [*paper in preparation*]
8. We established the home-built platforms for the zero- to ultralow-field (ZULF) NMR based on self-developed high-sensitivity atomic magnetometers. On the platform, we realized and benchmarked universal quantum control in ZULF NMR for the first time [*paper 23-25*]. We largely improved the detection sensitivity for ZULF NMR by developing gradiometric method [*paper 15* & Science Advances 7, eabe0719 (2021)]. We discovered the interference effect in the atomic magnetometers which explained a hitherto puzzling phenomenon of asymmetric spectroscopy in ZULF NMR. [*paper 09*]

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

The two teams will continue their collaborations on exploring the many-body correlations in spin systems using NMR experiments and the new quantum nonlinear spectroscopy approach. Moreover, the theoretical methods can be extended to other quantum systems. In particular, both the mainland team and the Hong Kong team are working on novel quantum light sources based on superradiance masing such as diamond maser and Floquet maser [with publications in *Nature Communications* (2015), *Science Advances* (2021), *Science* (2021), and *Nature* (2018) by the two teams]. The unconventional correlations in such novel quantum light sources can be used to detect the many-body correlations in spin systems which act as the superradiant quantum emitters. The combination of the approaches developed in this project and the novel hybrid spin-photon many-body systems can provide new opportunities of quantum metrology and quantum sensing. The two teams are considering to submit a new proposal for the joint scheme.

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)

All physical quantities must be real numbers. A recent discovery by the teams (published in 2015) enables simulation of a quantum system with complex physical parameters utilizing the quantum phase factor, which is a complex number. This approach makes it possible for the first time to study physics in the complex plane of parameters. That discovery motivated the two teams to explore quantum many-body dynamics under complex forces. In this project, the two teams collaborated to realize a novel approach to studying quantum dynamics under complex-numbered force. Usual classical force is a real number. The two teams found that if a quantum force is applied to a system through a quantum sensor, the nature of the force, being effectively real or imaginary, can be post-selected after the interaction through the choice of quantum measurement, which is made possible by the peculiar feature of quantum entanglement. They implemented the scheme using quantum control and readout of nuclear spins in nuclear magnetic resonance experiments and extracted higher order quantum correlations in nuclear spins, which would be inaccessible to classical probes. The methods developed in these schemes provide a new toolbox for studying quantum many-body physics.

<u>Part C: Research Output</u>

8. Peer-reviewed journal publication(s) arising <u>directly</u> 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)*						

01				For submission to Nature Physics	Ze Wu, Ping Wang, Yuchen Li, Tuanyun Wang, **Xinhua Peng*, Ren-Bao Liu***	Extraction of arbitrary quantum correlations using ensemble nuclear spin sensors	No	Yes	Yes RGC & NSFC	No
02				For submission to Phys. Rev. X	Weng Hang Leong, **Xinhua Peng, Ren-Bao Liu***	Dynamic quantum phase transitions in non-Hermitian systems	No	Yes	Yes RGC & NSFC	No
03		2021			Shiming Song, Min Jiang, Yushu Qin, Yu Tong, Wenzhe Zhang, Xi Qin, **Ren-Bao Liu, and Xinhua Peng***	Physical Review Applied (in press). Collision-induced spin noise	No	Yes	Yes RGC & NSFC	No
04	2021				Chong Chen*, Ping Wang, and **Ren-Bao Liu**	Physical Review A 104, L020601 (2021). Effects of local decoherence on quantum critical metrology	No	Yes	Yes RGC	Yes
05	2020				Chen, Qi-Ming*; Yang, Xiaodong; Arenz, Christian; Wu, Re-Bing; **Peng, Xinhua**; Pelczer, Istvan; Rabitz, Herschel	PHYSICAL REVIEW A 101, 032313 (2020). Combining the synergistic control capabilities of modeling and experiments: Illustration of finding a minimum-time quantum objective	No	Yes	Yes NSFC 11661161018	No
06	2020				Zhou, Hui; Ji, Yunlan; Nie, Xinfang; Yang, Xiaodong; Chen, Xi; Bian, Ji; **Peng, Xinhua***	Phys. Rev. Applied 13, 044059 (2020). Experimental realization of shortcuts to adiabaticity in a nonintegrable spin chain by local counterdiabatic driving	No	Yes	Yes NSFC 11661161018	No
07	2020				Chen, Jiahui; Zhou, Yehao; Bian, Ji; Li, Jun*; **Peng, Xinhua***	Physical Review A 102, 032602 (2020). Subspace controllability of symmetric spin networks	No	Yes	Yes NSFC 11661161018	No
08	2020				Yang, Xiao-dong; Arenz, Christian; Pelczer, Istvan; Chen, Qi-Ming; Wu, Re-Bing*; **Peng, Xinhua***; Rabitz, Herschel*	Physical Review A 102, 062605 (2020). Assessing three closed-loop learning algorithms by searching for high-quality quantum control pulses	No	Yes	Yes NSFC 11661161018	No
09	2020				Jiang, Min; Xu, Wenjie; Li, Qing; Wu, Ze; Suter, Dieter; **Peng, Xinhua***	Advanced Quantum Technologies 3, 2000078 (2020). Interference in Atomic Magnetometry	No	Yes	Yes NSFC 11661161018	No
10	2020				Yang, Xiaodong; Thompson, Jayne; Wu, Ze; Gu, Mile*; **Peng, Xinhua***; Du, Jiangfeng	npj Quantum Information 6, 62 (2020). Probe optimization for quantum metrology via closed-loop learning control	No	Yes	Yes NSFC 11661161018	No

11	2019				P. Wang, C. Chen, **Xinhua Peng**, J. Wrachtrup, and **Ren-Bao Liu***	Physical Review Letters 123, 050603 (2019). Characterization of arbitrary-order correlations in quantum baths by weak measurement	Yes, 2018-12-31	Yes	Yes RGC & NSFC	Yes
12	2019				Li, Zhaokai; Liu, Xiaomei; Wang, Hefeng*; Ashhab, Sahel; Cui, Jiangyu; Chen, Hongwei; **Peng, Xinhua***; Du, Jiangfeng*	Physical review letters 122, 090504 (2019). Quantum simulation of resonant transitions for solving the eigen problem of an effective water Hamiltonian	No	Yes	Yes NSFC 11661161018	No
13	2019				Wang, Hengyan; Ma, Zhihao; Wu, Shengjun; Zheng, Wenqiang; Cao, Zhu; Chen, Zhihua; Li, Zhaokai; Fei, Shao-Ming; **Peng, Xinhua***; Vedral, Vlatko; Du, Jiangfeng*	npj Quantum Information 5, 39 (2019). Uncertainty equality with quantum memory and its experimental verification	No	Yes	Yes NSFC 11661161018	No
14	2019				Zhu, Zhennan; Chen, Tao; Yang, Xiaodong; Bian, Ji; Xue, Zheng Yuan*; **Peng, Xinhua***	Physical Review Applied 12, 024024 (2019). Single-loop and composite-loop realization of nonadiabatic holonomic quantum gates in a decoherence-free subspace	No	Yes	Yes NSFC 11661161018	No
15	2019				Jiang, Min; Frutos, Roman Picazo; Wu, Teng*; Blanchard, John W; **Peng, Xinhua***; Budker, Dmitry	Physical Review Applied 11, 024005 (2019). Magnetic gradiometer for the detection of zero-to ultralow-field nuclear magnetic resonance	No	Yes	Yes NSFC 11661161018	No
16	2019				Ji, Yunlan; Bian, Ji; Chen, Xi; Li, Jun; Nie, Xinfang; Zhou, Hui*; **Peng, Xinhua***	Physical Review A 99, 032323 (2019). Experimental preparation of Greenberger- Horne-Zeilinger states in an Ising spin model by partially suppressing the nonadiabatic transitions	No	Yes	Yes NSFC 11661161018	No
17	2019				Yang, Xiaodong; Li, Jun*; **Peng, Xinhua***	Science Bulletin 64, 1402 (2019). An improved differential evolution algorithm for learning high-fidelity quantum controls	No	Yes	Yes NSFC 11661161018	No
18	2019				Zhou, Hui; Chen, Xi; Nie, Xinfang; Bian, Ji; Ji, Yunlan; Li, Zhaokai; **Peng, Xinhua***	Science bulletin 64, 888 (2019). Floquet-engineered quantum state transfer in spin chains	No	Yes	Yes NSFC 11661161018	No

19	2019				Bian, Ji; Chen, Xi; Liu, Ran; Zhu, Zhennan; Yang, Xiaodong; Zhou, Hui*; **Peng, Xinhua***	Physical Review A 100, 042315 (2019). Experimental observation of the effect of global phase on optimal times of SU(2) quantum operations	No	Yes	Yes NSFC 11661161018	No
20	2018				Wen-Long Ma, Ping Wang, Weng-Hang Leong, and **Ren-Bao Liu***	Phys. Rev. A 98, 012117 (2018). Phase transitions in sequential weak measurements	No	Yes	Yes RGC	Yes
21	2018				Zheng, Wenqiang; Ma, Zhihao; Wang, Hengyan*; Fei, Shao-Ming*; **Peng, Xinhua***	Phys. Rev. Lett., 120, 230504 (2018). Experimental demonstration of observability and operability of robustness of coherence.	No	Yes	Yes NSFC 11661161018	No
22	2018				J. Cui, J. Li, X. Liu, **X. Peng***, and R. Fu*	Journal of Magnetic Resonance, 294:83-92 (2018). Engineering spin Hamiltonians using multiple pulse sequences in solid state NMR spectroscopy.	Yes, 2018-12-31	Yes	Yes NSFC 11661161018	
23	2018				Jiang, Min; Wu, Teng*; Blanchard, John W*; Feng, Guanru; **Peng, Xinhua***; Budker, Dmitry	Science Advances 4, eaar6327 (2018). Experimental benchmarking of quantum control in zero-field nuclear magnetic resonance	No	Yes	Yes NSFC 11661161018	No
24	2018				Jiang, Min; Bian, Ji; Liu, Xiaomei; Ji, Yunlan; Zhang, Bo; **Peng, Xinhua***, Jiangfeng Du	Phys. Rev. A, 97, 062118 (2018). Numerical optimal control of spin systems at zero magnetic field	No	Yes	Yes NSFC 11661161018	No
25	2018				Ji Yunlan; Bian Ji; Jiang Min; D'Alessandro Domenico*; **Peng Xinhua***	Physical Review A 98, 062108 (2018). Time-optimal control of independent spin-1/2 systems under simultaneous control	No	Yes	Yes NSFC 11661161018	No
26	2017				Chon-Fai Kam & **Ren-Bao Liu***	Scientific Reports 7, 9756 (2017). 2 + 1 dimensional de Sitter universe emerging from the gauge structure of a nonlinear quantum system	No	Yes	Yes RGC	Yes
27	2017				Chen, Jiahui; Zhou, Hui; Duan, Changkui*; **Peng, Xinhua***	Physical Review A 95, 032340 (2017). Preparing Greenberger-Horne-Zeilinger and W states on a long-range Ising spin model by global controls	No	Yes	Yes NSFC 11661161018	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)*
01	Oct/2017 /Taiyuan, China	Quantum phase transitions in a non-Hermitian system	Symposium on Quantum Simulation	Yes, 2018-12-31	Yes	Yes	No
02	Jan/2018 /Shenzhen, China	Quantum phase transitions on the complex plane of a magnetic field	International Workshop on Physics of Information	Yes, 2018-12-31	Yes	Yes	No
03	May/2018 /Hangzhou, China	Phase transitions from weak to strong quantum measurement	The 9th International Workshop on Solid-State Quantum Computing	Yes, 2018-12-31	Yes	Yes	No
04	October/ 2018/Changsha, China	Experimental quantum simulations towards exotic many-body quantum physics with nuclear spins	Quantum International Frontiers 2018	Yes, 2018-12-31	Yes	Verbally acknowledged in the presentation	No
05	July/ 2018/Barcelona, Spain	Towards quantum simulation of exotic quantum many-body physics with nuclear spins	The 26th International Conference on Atomic Physics (ICAP 2018)	Yes, 2018-13-31	Yes	Verbally acknowledged in the presentation	No
06	May/2019/Nanjing, China	Correlations in a quantum bath of a central spin	Nanjing Forum on Superconducting Quantum Computer and System (NFSQCS)	No	Yes	Yes	No
07	May/2019/Hangzhou, China	Characterization of correlations in a quantum bath	Symposium on Quantum Computing and Quantum Optics II	No	Yes	Yes	No
08	Dec/2019/ Shanghai, China	Quantum phase transitions in the complex plane of a physical parameter	Fudan Mini-program on Non-Hermitian Topology and Dynamics	No	Yes	Yes	No

09	Jan/2020/Snowbird, UT, USA	Quantum sensing, sensing quantum	The 50th Winter Colloquium on the Physics of Quantum Electronics (PQE-2020)	No	Yes	Yes	No
10	Mar/2020/Hasselt, Belgium	Diamond sensing of magnetic, thermal, and mechanical properties of materials at nanoscale	2020 Hasselt Diamond Workshop 2020 (SBDD XXV) (11-13 Mar 2020)	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
1	WANG, Ning	PhD	1/08/2014	Jan 2019
2	TANG, Holun	MPhil	1/08/2016	Jul 2018
3	HE, Mingyuan	PhD	1/08/2013	Jul 2017
4	KAM, Chon Fai	PhD	1/11/2013	Oct 2017

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

PI Renbao Liu was awarded the Willis E. Lamb Award (2022) for his “original contributions to understanding and combating central spin decoherence and applications to quantum information technologies.”

PI Xinhua Peng was selected as one of the “Science and Technology Innovation Leaders” of the National "Ten Thousand Talents Program" (2019), from the Organization Department of the Central Committee of the CPC.

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]	27	10	0	0	