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	LIU, Renbao, Professor	PENG, Xinhua, Professor
Investigator (with title)		
Post	Professor, Director of Centre	Professor, Head of the
	for Quantum Coherence	Department of Modern
		Physics
Unit / Department /	Department of Physics, The	Department of Modern
Institution	Chinese University of Hong	Physics, University of Science
	Kong	and Technology of China
Contact Information	rbliu@cuhk.edu.hk	xhpeng@ustc.edu.cn
	+852-3943 6312	+86-551-63602439
Co-investigator(s)	N.A.	N.A.
(with title and		
institution)		

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.

NSFC/RGC 8 (Revised 01/18)

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 ⁸⁵Rb and ⁸⁷Rb 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.

Part C: Research Output

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.*)

	Т	he Lates	t Sta	atus of	Author(s)	Title and Journal/ Book	Submitt	Attach	Acknow	Acces
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			Nature	Xinhua Peng*,	sensors			&	
			Physics	Ren-Bao Liu*				NSFC	
02			For	Weng Hang Leong,	Dynamic quantum phase	No	Yes	Yes	No
			submissi	Xinhua Peng,	transitions in non-Hermitian				
			on to	Ren-Bao Liu*	systems			RGC	
			Phys.					&	
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03		2021		Shiming Song, Min	Physical Review Applied (in	No	Yes	Yes	No
				Jiang, Yushu Qin,	press).				
				Yu Tong, Wenzhe	Collision-induced spin noise			RGC	
				Zhang, Xi Qin,				&	
				Ren-Bao Liu, and				NSFC	
				Xinhua Peng*					
04	2021			Chong Chen*, Ping	Physical Review A 104,	No	Yes	Yes	Yes
				Wang, and	L020601 (2021). Effects of				
				Ren-Bao Liu	local decoherence on			RGC	
					quantum critical metrology				
05	2020			Chen, Qi-Ming*;	PHYSICAL REVIEW A	No	Yes	Yes	No
				Yang, Xiaodong;	101, 032313 (2020).				
				Arenz, Christian;	Combining the synergistic			NSFC	
				Wu, Re-Bing;	control capabilities of			11661	
				Peng, Xinhua;	modeling and experiments:			16101	
				Pelczer, Istvan;	Illustration of finding a			8	
				Rabitz,	minimum-time quantum				
				Herschel	objective				
06	2020			Zhou, Hui; Ji,	Phys. Rev. Applied 13,	No	Yes	Yes	No
				Yunlan; Nie,	044059 (2020).				
				Xinfang; Yang,	Experimental realization of			NSFC	
				Xiaodong; Chen,	shortcuts to adiabaticity in a			11661	
				Xi; Bian, Ji; Peng,	nonintegrable spin chain by			16101	
				Xinhua*	local counterdiabatic driving			8	
07	2020			Chen, Jiahui; Zhou,	Physical Review A 102,	No	Yes	Yes	No
				Yehao; Bian, Ji; Li,				NSFC	
				Jun*; Peng,	Subspace controllability of			11661	
				Xinhua*	symmetric spin networks			16101	
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08	2020			Yang, Xiao-dong;	Physical Review A 102,	No	Yes	Yes	No
				Arenz, Christian;	062605 (2020).		1	NSFC	
				Pelczer, Istvan;	Assessing three closed-loop			11661	
				Chen, Qi-Ming;	learning algorithms by			16101	
				Wu, Re-Bing*;	searching for high-quality			8	
				Peng, Xinhua*;	quantum control pulses				
				Rabitz, Herschel*					
09	2020			Jiang, Min; Xu,	Advanced Quantum	No	Yes	Yes	No
				Wenjie; Li, Qing;	Technologies 3, 2000078		1	NSFC	
				Wu, Ze; Suter,	(2020).		1	11661	
				Dieter; Peng,	Interference in Atomic		1	16101	
				Xinhua*	Magnetometry			8	L
10	2020			Yang, Xiaodong;	npj Quantum Information 6,	No	Yes	Yes	No
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				Peng, Xinhua*;	quantum metrology via			16101	
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12 2019 Li, Zhaokai; Liu, Xiaomei; Wang, Hefeng*; Ashhab, Sahel; Cui, Jiangyu; Peng, Xinhua*; Du, Jiangfeng* No Yes Yes 13 2019 Wang, Hengyan; Nam, Zhihao; Yuu, Shengjun; Cao, Zhu; Chen, Zhihua; mailtonian No Yes Yes 13 2019 Wang, Hengyan; Du, Jiangfeng* npj Quantum Information 5, No No Yes Yes 13 2019 Wang, Hengyan; Shao-Ming; Peng, Xinhua*; Vedral, Vlatko; Du, Jiangfeng* npj Quantum Information 5, No No Yes Yes 14 2019 Zhu, Zhennan; Chen, Tao; Yang, Xiaodong; Bian, Ji; Single-loop and composite- Xue, Zheng Yuan*; Peng, Xinhua*; Peng, Xinhua*; Peng, Xinhua*; Budkar, John W; Peng, Xinhua*; Pung, Xinhua*; Peng, Xinhua*; Pung, Xinhua*;				Characterization of	12-31		&	
12 2019 Li, Zhaokai; Liu, Ziaomei; Wang, Hefeng*; Ashhab, Sahel; Cui, Jiangyu; resonant transitions for Sahel; Cui, Jiangyu; resonant transitions for Solving the eigen problem of Sahel; Cui, Jiangteng* No Yes Yes 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, Sp (2019). No Yes Yes 14 2019 Zhu, Zhennan; Chen, Zhihua; Vlatko; Du, Jiangfeng* Physical Review Applied It. (2024) (2019). No Yes Yes 15 2019 Jiang, Min; Frutos, Peng, Xinhua*; Bedigan, Jiang, Min; Frutos, Physical Review Applied It. (2024) (2019). No Yes Yes 16 2019 Jiang, Min; Frutos, Peng, Xinhua*; Bedge, Ultradigation of genetization of John W: Peng, Xinhua*; Budker, Ultradigation of John W: Peng, Xinhua*; Budker, Ultradigation of John W: Peng, Xinhua*; Budker, Ultradigation of Ziangenetic resonance No Yes Yes 16 2019 Jiang, Min; Frutos, Physical Review Applied Jianghabac It. (2040) (2019). No Yes Yes 17 2019 Jiang, Min; Frutos, Physical Review A99, Ohe, Xinfang; Zhou, Ultradigation of Greenberger- Horne-Zieilinger states in an Ising spin model by partially suppressing the nonadiabatic transitions No Yes Yes			Ren-Bao Liu*	arbitrary-order correlations			NSFC	
12 2019 Li, Zhaokai; Liu, Xiaomei; Wang, Hefeng*, Ashhab, Sahel; Cui, Jiangyu; Chen, Hongwei; Du, Jiangfeng* Physical review letters 122, 090504 (2019). No Yes NSFC 13 2019 Wang, Hengyan; Du, Jiangfeng* no effective water Hamiltonian no effective water Hamiltonian No Yes NSFC 13 2019 Wang, Zhinbua*; Du, Jiangfeng* no effective water Hamiltonian No Yes Yes 14 2019 Zhu, Zhennan; Chen, Tao; Yang, Xiabua*; Vedral, Vlatko; Du, Jiangfeng* Physical Review Applied Chen, Tao; Yang, Xiabua*; Vedral, Vlatko; Du, Jiangfeng* Physical Review Applied Chen, Tao; Yang, Xiabua*; Vedral, Vlatko; Du, Jiangfeng* No Yes Yes 14 2019 Jiang, Min; Frutos, Roman Picazo; Wu, Xinbua*; Budker, Dinty Physical Review Applied Chen, Xi; Li, Jun; Nongretication of nonadiabatic holonomic quantum gates in a decoherence-free subspace No Yes Yes 15 2019 Jiang, Min; Frutos, Roman Picazo; Wu, Xinbua*; Budker, Dinty Physical Review A99, No No Yes Yes 16 2019 Jiang, Min; Frutos, Roman Picazo; Wu, Roman Pi				in quantum baths by weak				
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		Zhennan; Yang,	Experimental observation of			11661	
		Xiaodong; Zhou,	the effect of global phase on			16101	
		Hui*; Peng,	optimal times of $SU(2)$			8	
		Xinhua*	quantum operations				
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		Ping Wang,	(2018).			RGC	
		Weng-Hang Leong,	Phase transitions in				
		and Ren-Bao Liu*	sequential weak				
			measurements				
21	2018	Zheng, Wenqiang;	Phys. Rev. Lett., 120,	No	Yes	Yes	No
			230504 (2018).			NSFC	
		Hengyan*; Fei,	Experimental demonstration			11661	
		Shao-Ming*; Peng,	of observability and			16101	
		Xinhua*	operability of robustness of			8	
			coherence.			-	
22	2018	J. Cui, J. Li, X. Liu.	Journal of Magnetic	Yes,	Yes	Yes	
		X. Peng*, and R.	Resonance, 294:83-92	2018-		NSFC	
		Fu*	(2018).	12-31		11661	
			Engineering spin			16101	
			Hamiltonians using multiple			8	
			pulse sequences in solid				
			state NMR spectroscopy.				
23	2018	Jiang, Min; Wu,	Science Advances 4,	No	Yes	Yes	No
-		Teng*; Blanchard,	eaar6327 (2018).			NSFC	
		John W*; Feng,	Experimental benchmarking			11661	
		Guanru; Peng ,	of quantum control in			16101	
		Xinhua*; Budker,	zero-field nuclear magnetic			8	
		Dmitry	resonance				
24	2018	Jiang, Min;	Phys. Rev. A, 97, 062118	No	Yes	Yes	No
		Bian, Ji; Liu,	(2018).			NSFC	
		Xiaomei; Ji,	Numerical optimal control			11661	
			of spin systems at zero			16101	
		Peng, Xinhua*,	magnetic field			8	
75	2018	Jiangfeng Du	Discologia Descience A 00	Ma	Ver	Var	NT-
23	2018	Ji Yunlan; Bian Ji;	Physical Review A 98,	No	Yes	Yes	No
		Jiang Min;	062108 (2018).			NSFC	
		D'Alessandro	Time-optimal control of			11661	
		Domenico*; Peng	independent spin-1/2			16101	
		Xinhua*	systems under simultaneous			8	
\mathbf{r}	2017	Chon-Fai Kam &	control Scientific Reports 7, 9756	No	Yes	Yes	Yes
20	2017	Chon-Fai Kam & Ren-Bao Liu*	(2017).	INO	res	r es RGC	les
		Nell-Day Liu*	(2017). 2 + 1 dimensional de Sitter			NOC	
			universe emerging from the				
			gauge structure of a				
27	2017	Chan Jinhui 7hou	nonlinear quantum system Physical Review A 95,	No	Yes	Yes	No
21	2017		•	100	res		
		Hui; Duan,	032340 (2017).			NSFC	
		Changkui*; Peng ,	Preparing Greenberger-			11661	
		Xinhua*	Horne-Zeilinger and W			16101	
			states on a long-range Ising			8	
			spin model by global				
	1 1 1		controls	1	1	1	1

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	ed to RGC (indicate the year ending of the relevant progress report)	No)	wledge d the support of this Joint Resear ch Schem e (Yes or No)	ble from the instituti onal reposit ory (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
	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
	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		Experimental quantum simulations towards exotic many-body quantum physics with nuclear spins	Quantum International Frontiers 2018	Yes, 2018-12 -31	Yes	Verball y ackno wledge d in the present ation	No
05	a, 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	Verball y ackno wledge d in the present ation	
	May/2019/Na njing, China	Correlations in a quantum bath of a central spin	Nanjing Forum on Superconducting Quantum Computer and System (NFSQCS)	No	Yes	Yes	No
	ngzhou, China	Characterization of correlations in a quantum bath	Symposium on Quantum Computing and Quantum Optics II	No	Yes	Yes	No
	Dec/2019/ Shanghai, China	Quantum phase transitions in the complex plane of a physical parameter	1 0	No	Yes	Yes	No

09	Jan/2020/Sno	Quantum sensing,	The 50th Winter	No	Yes	Yes	No
	wbird, UT,	sensing quantum	Colloquium on the				
	USA		Physics of Quantum				
			Electronics (PQE-2020)				
10	Mar/2020/Has	Diamond sensing of	2020 Hasselt Diamond	No	Yes	Yes	No
	selt, Belgium	magnetic, thermal, and	Workshop 2020 (SBDD				
		mechanical properties of	XXV) (11-13 Mar 2020)				
		materials at nanoscale					

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	