RGC Ref.: A-CUHK403/15
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The Research Grants Council of Hong Kong
ANR/RGC Joint Research Scheme
Completion Report

(Please attach a copy of the completion report submitted to the ANR by the French researcher)

Part A: The Project and Investigator(s)

1. Project Title (ANR Acronym)

Quantum Information Processing with Spin Ensembles (QIPSE)

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

	Hong Kong Team	French Team
Name of Principal Investigator *(with title)*	Renbao Liu, Prof.	Patrice Bertet, Dr.
Post	Professor, Director of Centre for Quantum Coherence	Researcher
Unit / Department / Institution	Department of Physics, The Chinese University of Hong Kong	Quantronics group, SPEC, CEA Saclay
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Co-investigator(s) *(with title and institution)*		Denis Vion, Dr.

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted)*
Project Start date	1 Mar 2016	N.A.	
Project Completion date	29 Feb 2020	N.A.	
Duration *(in month)*	48	N.A.	
Deadline for Submission of Completion Report		N.A.	

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. Spin-ensemble quantum memory for superconducting qubits
2. Understand and improve spin coherence time
3. Quantum simulation of quantum many-body physics based on spin ensembles

5.2 Revised Objectives

Date of approval from the RGC: ____________________

Reasons for the change: ____

6. Research Outcome

Major findings and research outcome

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

1) Microwave Quantum memory

We constructed and demonstrated a quantum memory based on ensemble spins of bismuth donors in silicon and Erbium-doped crystals, coupled to superconducting resonators.

W*ell-defined Rabi rotations* – Using pulse optimization [4, 7] and shallow implantation to mitigate the inhomogeneity of control field, we achieved nearly ideal refocusing pulses [12].

Characterization by spin spectroscopy – We characterized and understood of the spin spectrum of bismuth donors in silicon using EPR spectroscopy with the micro-resonator [5, 6, 13]. We measured the local nuclear spin environment by measuring the Electron Spin Echo Envelope Modulation (ESEEM), both for bismuth donors in silicon as well as for Erbium ions in a CaWO4 crystal [11]. In a Bi:Si sample, we observed location-dependent spin decoherence due to the local strain [13].

Long coherence times (300 ms) were observed by measuring bismuth donor spins at a clock [9,13], the longest coherence time reported for electron spins in a nanostructure. We have also performed a systematic coherence time study of Erbium-doped CaWO4 for various temperatures and doping concentrations [12].

Long-term storage of quantum microwave fields - We demonstrated the storage of quantum microwave fields in an ensemble of bismuth donors in silicon biased at a clock transition, for up to 100ms, and retrieved with a 10^{-3} efficiency, which is an improvement of storage time over the previous state-of-the-art by 3 orders of magnitude.

2) **Ultra-high sensitivity EPR spectroscopy**

Related results were obtained on improving the sensitivity of EPR spectroscopy using superconducting resonators and amplifiers. First, we used optimized resonator geometry to push the spin detection volume as low as femtoliters [2,10]. Then, we also did an experiment demonstrating that using quantum squeezing it is possible to push the sensitivity beyond the limit imposed by vacuum fluctuations of the microwave field [3].

3) Modified cluster-correlation expansion (CCE) and real-space renormalization theory

We developed a modified CCE theory for decoherence of clock-transitions in spin baths. The numerical simulation shows that the modified CCE converges rapidly for the CTs. The method can also be applied to other important problems such as the decay of Rabi oscillations and rotary echo [14].

CCE theory at the ultra-long timescales - Usually the cluster expansion theories fail with decreasing temperature in thermodynamics or increasing time in dynamics due to the emerging of larger clusters. We discovered surprisingly that the 2nd order CCE, if an effective dissipation rate is considered for the cluster correlation, reproduces very well the experimental data. We found that the higher-order correlations amount to a renormalized frequency (including both real and imaginary parts) of the CCE-2 processes [16].

Quantum tensor network theory for spin baths with long-range correlations - For qubit decoherence in long timescales or in relatively small spin baths, an interesting question is the growth of long-range correlations. The theoretical description of the long-range correlations, however, is challenging. The CCE method fails to account for the long-range correlation. We formulated a real-space renormalization method particularly suitable for studying the dynamics of random quantum networks and hence for studying qubit decoherence in such baths. The method is based on a quantum tensor network description of the states of the baths. Comparison between exact numerical solutions and the tensor network method demonstrates a promising theory [15].

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

The real-space renormalization theory for spin bath dynamics based on quantum tensor networks provides a natural identification of “nodes” in a complex quantum spin network (as the nodes of the tree tensor network that simulates the spin bath). We expect further theoretical and experimental studies can develop new methods to control the bath dynamics more efficiently using the manipulation of the node spins. For example, the correlation growth and the entanglement propagation in a spin bath can be controlled by flip-flopping only one or a few node spins. The tensor network formalism may also be used for machine-learning some small spin networks, which is useful for quantum memory and small-scale quantum computing.

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)

A quantum computer consists of quantum bits, on which complex quantum states manipulation are performed. Because quantum states collapse in realistic environments, it is desirable to store quantum information in a memory with long storage time. The main objective of QPISE is to progress towards a quantum memory compatible with superconducting quantum processors, a main candidate for quantum computing.

We build the quantum memory with an ensemble of bismuth donor spins in silicon, coupled to a superconducting micro-resonator, which operates at millikelvin temperatures. We demonstrated the storage of microwave photons over 100 milliseconds, an improvement over the state-of-the-art by 3 orders of magnitude.

The collapse of quantum states, called decoherence, is the major obstacle in building quantum memories. A dominating mechanism of decoherence is the many-body interaction in the environments in which the quantum memory is situated. It is therefore important to understand the many-body physics for the decoherence of quantum bits. In this project, we have constructed quantum many-body theories suitable for studying the ensemble spin decoherence in the optimal memory parameter regimes (namely, near so-called clock-transitions) and also formulated a real-space renormalization theory for calculating spin decoherence in a complex quantum network, using the tensor network renormalization.

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.)

Reference No.	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)*						
1	2016				C. Grezes, Y. Kubo, B. Julsgaard, T. Umeda, J. Isoya, H. Sumiya, H. Abe, S. Onoda, T. Ohshima, K. Nakamura, I. Diniz, A. Auffeves, V. Jacques, J.-F. Roch, D. **Vion, D.** Esteve, K. Moelmer, and **P. Bertet***	Towards a spin- ensemble quantum memory for super-conducting qubits. Comptes Rendus Physique 17, 693	No	Yes	Yes*	No
2	2017				S. Probst, A. Bienfait, P. Campagne-Ibarcq, J.J. Pla, B. Albanese, J.F. Da Silva Barbosa, T. Schenkel, **D. Vion**, D. Esteve, K. Moelmer, J.J.L. Morton, R. Heeres, **P. Bertet***	Inductive-detection electron-spin resonance spectroscopy with 65 spins/√Hz sensitivity. Appl. Phys. Lett. 111, 202604	No	Yes	Yes*	No
3	2017				A. Bienfait, P. Campagne-Ibarcq, A.H. Kiilerich, X. Zhou, S. Probst, J. J. Pla, T. Schenkel, **D. Vion**, D. Esteve, J.J.L. Morton, K. Moelmer, **P. Bertet***	Magnetic Resonance with Squeezed Microwaves. Phys. Rev. X 7, 041011	No	Yes	Yes*	No
4	2018				Q. Ansel, S. Probst, **P. Bertet,** S.J. Glaser, D. Sugny	Optimal control of an inhomogeneous spin ensemble coupled to a cavity, Phys. Rev. A 98, 023425	No	Yes	Yes*	No
5	2018				P. Conti, Z. Zeng, J. J. Pla, **P. Bertet**, M. W. Swift, C. G. Van de Walle, M. L. W. Thewalt, B. Sklenard, Y. M. Niquet, and J. J. L. Morton	Linear Hyperfine Tuning of Donor Spins in Silicon Using Hydrostatic Strain, J. Mansir, Phys. Rev. Lett. 120, 167701	No	Yes	Yes*	No
6	2018				J.J. Pla, A. Bienfait, G. Pica, J. Mansir, F.A. Mohiyaddin, Z. Zeng, Y.M. Niquet, A. Morello, T. Schenkel, J.J.L. Morton, and **P. Bertet***	Strain-induced spin-resonance shifts in silicon devices, Phys. Rev. Appl. 9, 044014	No	Yes	Yes*	No
7	2019				S. Probst, V. Ranjan, Q. Ansel, R. Heeres, B. Albanese, E. Albertinale, **D. Vion**, D. Esteve, S.J. Glaser, D. Sugny, and **P. Bertet***	Shaped pulses for transient compensation in quantum-limited electron spin resonance spectroscopy, Journal of Magnetic Resonance 303, 42-47	No	Yes	Yes*	No
8	2020				A. A. Clerk, K. W. Lehnert, **P. Bertet**, J. R. Petta & Y. Nakamura	Hybrid quantum systems with circuit quantum electrodynamics, Nature Physics 16, 257	No	Yes	Yes*	No
9	2020				V. Ranjan, J. O'Sullivan, E. Albertinale, B. Albanese, T. Chanelière, T. Schenkel, **D. Vion,** D. Esteve, E. Flurin, J. J. L. Morton, **P. Bertet***	Multimode storage of quantum microwave fields in electron spins over 100 ms, Phys. Rev. Lett. 125, 210505	No	Yes	Yes*	No

10	2020				V. Ranjan, S. Probst, B. Albanese, T. Schenkel, **D. Vion**, D. Esteve, J. J. L. Morton, and **P. Bertet***	Electron spin resonance spectroscopy with femtoliter detection volume, Appl. Phys. Lett. 116, 184002	No	Yes	Yes*	No
11	2020				S. Probst, G. L. Zhang, M. Rancic, V. Ranjan, M. Le Dantec, Z. Zhong, B. Albanese, A. Doll, **R. B. Liu**, J. J. L. Morton, T. Chanelière, P. Goldner, **D. Vion**, D. Esteve, **P. Bertet***	Hyperfine spectroscopy in a quantum-limited spectrometer, Magn. Reson., 1, 315–330	No	Yes	Yes	No
12				Yes	M. Le-Dantec, M. Rancic, S. Lin, P. Goldner, T. Chanelière, S. Bertaina, E. Flurin, D. Esteve, **D. Vion**, **R. Liu**, **P. Bertet***	20-millisecond spin coherence times in an Erbium-doped crystal, in preparation (2020)	No	No	Yes	No
13			Yes		V. Ranjan, E. Albertinale, E. Billaud, C. Zollitsch, T. Schenkel, J. Morton, J. Pla, D. Esteve, **D. Vion**, E. Flurin, **P. Bertet***	Spatially-resolved decoherence of donor spins in silicon strained by a metallic electrode, arxiv:2101.04391, submitted to Phys. Rev. X (2021)	No	No	Yes*	No
14	2020				G. L. Zhang, W. L. Ma, and **R. B. Liu***	Cluster-correlation expansion for studying decoherence of clock transitions in spin baths, Phys. Rev. B 102, 245303	No	Yes	Yes	No
15				Yes	Chong Chen and **R. B. Liu***	Quantum tensor network theory of central spin decoherence in spin baths, in preparation (2021)	No	No	Yes	No
16				Yes	Sen Lin and **R. B. Liu***	Cluster-correlation expansion study of rare earth spin decoherence in the ultra-long timescales, in preparation (2021)	No	No	Yes	No
17	2017				Wen Yang, Wen-Long Ma, and **Ren-Bao Liu***	Reports on Progress in Physics 80, 016001 (2017). Quantum many-body theory for electron spin decoherence in nanoscale nuclear spin baths.	Yes 2018	No	No	No

* *These outputs are produced by the French partner, which acknowledged the support by the QIPSE (but not explicitly the RGC).*

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)*
Jul 2018, Montpellier, France	Diamond sensing of the phase transition of a single magnetic nanoparticle and criticality-enhanced nano-thermometry	The 34th International Conference on the Physics of Semiconductors (ICPS2018)	No	Yes	Yes	No
Sep 2019, Safed, Israel	Decoherence of a rare-earth spin near the zero first-order Zeeman shift point	Workshop on Impurity Spins for Quantum Information & Technologies	No	Yes	Yes	No
October 2018, Saclay, France	NV center spin decoherence at low field and Overhauser field locking	Workshop on Spin Impurities in Solid for Quantum Technologies	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
ZHANG, Gengli	PhD	1 Aug 2015	21 Jun 2020

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

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	13	3	0	0	