Project number: ___T45-406/23-R___

RESEARCH GRANTS COUNCIL
THEME-BASED RESEARCH SCHEME (TRS)

Completion Report on Funded Project

Project start date: *1 January 2024*
Project completion date: *31 December 2024*

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1. Project Title: Diamond-based Multi-modal Quantum Sensing of Nanomagnetism

2. Names and Academic Affiliations of Project Team Members#

Project team member	Name / Post	Unit / Department / Institution	Average number of hours per week spent on this project in the whole project period
Project Coordinator (PC)	Liu, Renbao / Professor/ Director	The Hong Kong Institute of Quantum Information Science and Technology/ Dept. Physics /CUHK	12
Co-Principal Investigator(s)	Li, Quan/ Professor	Dept. Physics/CUHK	8
	Lu, Jian/ Professor/ Director	Dept. Biomedical Science, Dept. Material Science and Engineering, and Dept. Mechanical Engineering/ Hong Kong Branch of National Precious Metals Material Engineering Research Center/Centre for Advanced Structural Materials/ CityU	4

	Lu, Yang/Professor	Dept. Mechanical Engineering/HKU	7
	Cui, Xiaodong/ Professor	Department of Physics/HKU	5
	Chiribella, Giulio/ Professor & Associate Head (Research)/ Director/ Professor (by courtesy)	Dept. Computer Science/Quantum Information & Computation Initiative, Dept. Computer Science/ HKU Department of Physics/ HKU	5
	Wang, Jiannong/ Chair Professor, Wu Chien-Shiung Professor of Science, Head	Dept. Physics/HKUST	5
Co-Investigator(s)			
Collaborators	Wrachtrup, Jörg/ Professor and Director	The 3rd Physical Institute/ University of Stuttgart	N.A.
	Nie, Yuefeng/ Professor	National Lab of Solid-State Microstructures & College of Engineering & Applied Sciences/ Nanjing University	N.A.

\# *Please highlight the approved changes in the project team composition and quote the date when the RGC granted approval of such changes. For changes in the project team composition, please submit a separate request, together with the justification and the curriculum vitae of the new member(s), to the RGC three months prior to the intended effective date of the change.*

3. Project Objectives

Summary of objectives addressed/achieved:

Objectives*	Percentage achieved	Remarks**
1. An integrated sensing platform	100%	
2. A framework of quantum information theories of sensitivity under realistic conditions.	100%	
3. Exploratory results on mechanical, structural, and magnetic properties of magnetic nanomaterials achieved using the integrated platform.	100%	

* *Please highlight the approved changes in objectives and quote the date when the RGC granted approval of such changes.*

** *Please provide reasons for significantly slower rate of progress than originally planned.*

6. Research Highlights and Outputs

6.1 What are the most exciting research accomplishments of the project?

(Please list <u>*five or more*</u> *of the team's best research accomplishments, such as journal and conference papers, software codes, research infrastructure, etc. For each item, please clearly justify how it has achieved international excellence (e.g. best paper award, invited presentation, citations, product licensed to industry, etc.))*

(1) We have set up the **AFM-ODMR platform** that integrates an atomic force microscope (AFM) with a confocal microscope-based optically detected magnetic resonance (ODMR) system. This platform is the first of its kind in the world with unique capability of performing nano-magnetometry of thin-film or 2D magnetic materials under nano-indentation. Measurement of the magnetization in the bulk of thin-film or two-dimensional materials is important for understanding their intrinsic properties without the complications from edges or domain walls. However, the stray fields from the bulk vanish or are very weak, which limits the application of direct measurement methods. The AFM-ODMR platform provides a non-destructive approach to directly measuring the stray fields from the bulk of thin-film magnets at arbitrarily designatable locations, with nanoscale spatial resolution. We employ nano-indentation to induce the leakage of stray fields from the materials and use nano-diamond magnetometers to measure them. We applied the method to Fe thin films and demonstrated the measurement of magnetization in the bulk of the materials and identified the different magnetization in different domains. The approach is broadly applicable to atomically thin magnets and can also be employed to study mechanical effects on magnetization. The measurement yields direct information about the intrinsic properties of the thin-film magnets free of the complications of edges.

(2) We upgraded an integrated diamond-based **high-temperature quantum sensing platform**. This setup is the only one in the world that can perform quantum sensing at high temperatures. Using this unique setup, we achieved quantum control at temperatures as high as above 1400 K. Maintaining and controlling quantum coherence at high temperature is not only of interest to addressing the fundamental question about the boundary between the quantum and classical worlds, but also useful for practical application such as quantum sensing of materials. We demonstrated optical detection of magnetic resonance of nitrogen-vacancy centres in diamond up to 1400 Kelvin, with the spins polarized and read out at room temperature and controlled at elevated temperatures by rapid heating and cooling. This temperature is higher than Cuire temperatures of all known materials. We measured temperature-dependent spin relaxation and Rabi oscillation at the largest temperature ranges. Such high-temperature quantum control can facilitate the exploration of a broad range of thermal phenomena, such as magneto-structural transitions, thermoremanent magnetism in rock particles, heat-assisted magnetic recording, thermo-plasmonic of nanoparticles, and thermal management using two-dimensional materials.

(3) We developed novel measurement setups exploiting coherent superpositions of different configurations, providing a way to enhance the measurement sensitivity with fewer samples. One of our methods allows for the efficient estimation of the so-called weak values, introduced by Yakir Aharonov and collaborators. Measuring weak values is known to enhance the precision of many sensing schemes, but most existing methods require weak interactions and postselection, or require a large number of samples, in the worst case growing exponentially with the number of particles in the system. In our work we developed a deterministic scheme for estimating weak values of arbitrary observables

with a constant number of samples, independent of the number of particles. This method applies to both pure and mixed states and is robust under noise, enabling weak value estimation under realistic laboratory conditions. At the fundamental level, it provides new insights into the relation between states of two identical quantum systems at the same moment of time and states of a single quantum system at two subsequent moments of time.

(4) We developed a framework for detecting a new type of quantum resource, known as input-output indefiniteness. Input-output indefiniteness takes place when a physical system (e.g. a photon) enters in a device in a coherent superposition of different directions, so that it becomes impossible in principle to identify an input and an output port. In our work, we show that input-output indefiniteness can enhance the precision of measurements, and, in turn, we construct a general measurement framework for detecting input-output indefiniteness with maximum sensitivity. The theory has been complemented by an experimental demonstration, done in collaboration with the group of Prof. Biheng Liu at USTC, where the detection of input-output indefiniteness was confirmed by more than 69 standard deviations.

(5) Finally, we explored the application of quantum measurement setups to quantum communication. In particular, we showed that quantum measurements, and classical data-processing can be used to simulate a quantum processes with higher efficiency that it was previously found. This method, called "shadow simulation of quantum processes" is a based on measurement data from multiple observables, and generalizes the method of quantum error mitigation. By paying an overhead in terms of samples, we showed that shadow simulation enables the simulation of a perfect noiseless process from a noisy one. In certain situation, it can even be used to simulate the transmission of a higher-dimensional system by actually sending a lower-dimensional system.

6.2 What was the added value of the TRS funding, rather than standard project grant funding?
(For example, could this work have been achieved with other funding scheme, such as the General Research Fund or Collaborative Research Fund? If not, why?)

This TRS exploratory project has enabled inter-disciplinary and inter-institutional collaborations that cannot be achieved by a regular RGC project. The collaborations involved expertise in material sciences, optics, quantum sensing, microscopy, and condensed matter physics. With only one year, we have achieved the integration of two multi-modal quantum sensing platforms, one combining nano-indentation, nano-manipulation, and quantum nano-magnetometry, and another with capability of world-record high-temperature quantum sensing. We have also conducted prototype sensing studies using the platforms.

The research of this project also prepared us to successfully secured a Ministry of Science and Technology of China 2030 project – the Quantum Science and Technology-National Science and Technology Major Project (Ref. 2023ZD0300600, 1 Jan 2024 – 31 Dec 2028, RMB18,000,000 allocated, with title "Study of critical nanomagnetism using diamond-based quantum sensing). Four members of the TRS project team are co-PIs of the MOST 2030 project.

We have also established the State Key Laboratory of Quantum Information Technologies and Materials (the SKL), with PC and two Co-PIs of the TRS project being members of the SKL.

All these achievements and large-scale collaborations have benefited critically from the collaborations in this TRS project. And the collaborations are continuing in these new projects.

6.3 If the project has not met its original objectives, why?

N.A.

6.4 (a) Please provide details of each peer-reviewed journal publication arising directly from this project by completing the table at **Annex** *(one for each publication)*.

(b) Please provide details of recognised international conference(s) in which paper(s) related to this project was/were delivered by completing the following table:
(Please attach a copy of each conference abstract)

Month/Year/ Place	Title	Conference name	Submitted to the RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of the RGC *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
06/2025/Hungary	Quantum sensing of intrinsic magnetization in thin-film magnets	The 33rd Annual International Laser Physics Conference	Submitted	Yes	Yes	Yes
06/2025/Shanghai	Solution of open quantum system problems	The Third International Conference on Quantum Frontiers	Submitted	Yes	Yes	Yes
12/2024/Guangzhou	Tackling the problem of open quantum systems	固态量子信息国际前沿研讨会 (IWSQI2024)	Submitted	Yes	Yes	Yes
11/2024/Nanjing	On the complexity of the open quantum system problem	The 2nd Nanjing Conference on Quantum Materials	Submitted	Yes	Yes	Yes
11/2024/Zhejiang	Tackling the problem of open quantum systems	量子计算与量子光学国际研讨会 (QCQO)	Submitted	Yes	Yes	Yes
09/2024/Japan	Tackling the problem of central spin decoherence	Spin Chemistry Meeting 2024	Submitted	Yes	Yes	Yes
07/2024/Shantou	Central spin problem – fundamentals and applications	南澳科学会议	Submitted	Yes	Yes	Yes

(c) RGC funding should have been acknowledged in all publication(s)/conference papers listed in (a) and (b) above. If no acknowledgement has been made in any of the publications/ papers, please indicate and provide explanations.
N.A.

6.5 To what extent this project has strengthened inter-institutional collaborations and other partnerships?

The collaborations involved expertise in material sciences, optics, quantum sensing, microscopy, and condensed matter physics. The successful setup of the integrated platforms and the investigation of Fe nano-flakes under nano-indentation have strengthened the collaborations between HKU (on processing of 2D materials, optical measurement of magnetic materials, and quantum sensing theory), HKUST (on processing of 2D and thin-film materials), CityU (on growth of nano-textured magnetic materials), CUHK (on diamond-based quantum sensing), and external collaborators including Professor Hou Yanglong in Peking University (on the fabrication of Fe nano-flakes), Professor Nie Yuefeng in Nanjing University (on fabrication of atomic thick magnetic materials) and Professor Wrachtrup in the University of Stuttgart (on fabrication of diamond nano-pillars with highly coherent nitrogen-vacancy centres and isotopically purified diamond samples). These collaborations have resulted in significant progress in developing quantum sensing platforms and methods and applications in materials science.

The collaborations also led to new large-scale projects including a Ministry of Science and Technology of China 2030 project – the Quantum Science and Technology-National Science and Technology Major Project and the recent establishment of the State Key Laboratory of Quantum Information Technologies and Materials (the SKL). In particular, the SKL will be a new platform for collaborations on quantum information science and technology among Hong Kong scientists and provide a bond to enhance the collaborations between Hong Kong and mainland China as well as the international community.

6.6 Research students trained (registration/awards):

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
Xi, LIU	MPhil	08/2022	02/2025
Li, SUN	PhD	08/2021	10/2025
Ma, CHEN	PhD	02/2024	01/2027 (estimated)
Junzheng, CHEN	PhD	09/2021	10/2025
Jingzhuo, ZHOU	PhD	09/2020	03/2025

6.7 Specific products (e.g. software or netware, instruments or equipment developed):

N.A.

6.8 Other education activities and/or training programmes developed:

N.A.

6.9 Please highlight any deliverables indicated in the project implementation timetable endorsed by the RGC which have not been covered or achieved as per sections 6.1 to 6.8 above, and explain/ elaborate.

N.A.

Project Management

6.10 Please elaborate how the PC has played his/her role in coordinating and managing the project.

PC has organized the collaborations between CUHK and the other three participating institutions, with coordinated meetings and workshops. He also led the research on the setup of the two quantum sensing platforms (AFM-ODMR and high-temperature quantum sensing) and the quantum sensing studies with the two platforms. PC acquired the samples from external collaborators (Professor Nie Yuefeng and Professor Wrachtrup).

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7. Awards and Recognition

7.1 Have any research grants been awarded that are directly attributable to the results obtained from this project?

Ministry of Science and Technology of China 2030 project – **the Quantum Science and Technology-National Science and Technology Major Project** (Ref. 2023ZD0300600, 1 Jan 2024 – 31 Dec 2028, RMB18,000,000 allocated), "Study of critical nanomagnetism using diamond-based quantum sensing). PC: Renbao Liu; Co-PIs from the TRS project: Quan Li, Giulio Chiribella

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7.2 Have any project team members participated as invited speakers in or organisers of international conferences as a result of this project?

(1) Professor has given invited/plenary talks in a number of prestigious international conferences, including

- Ren-Bao Liu, Plenary talk, The 33rd Annual International Laser Physics Conference (LPHYS'25) (30 Jun – 4 Jul 2025, Szeged, Hungary). A quantum upgrade of nonlinear spectroscopy
- Ren-Bao Liu, QDiamond 2025 (24-27 Feb 2025, Mátraháza, Hungary). Quantum nonlinear spectroscopy via a single spin quantum sensor
- Ren-Bao Liu, The 827th Wilhelm and Else Heraeus Seminar (3 – 6 Feb 2025, Bad Honnef, Germany). Diamond sensors in complex environments
- Ren-Bao Liu, Plenary talk, The 54th Winter Colloquium on the Physics of Quantum Electronics (PQE-2025) (5 – 10 Jan 2025, Snowbird UT, USA). Nanodiamond-based imaging and sensing for biology and materials sciences
- Ren-Bao Liu, The 36th International Conference on the Physics of Semiconductors (ICPS2024) (28 Jul – 2 Aug 2024, Ottawa, Canada). Quantum nonlinear spectroscopy via a single spin quantum sensor
- Ren-Bao Liu, The 32nd Annual International Laser Physics Workshop (LPHYS'24) (July 3 to 9, 2024, São Carlos, Brazil), Imaging, tracking and magnetic resonance of nanodiamond sensors in liquids
- Ren-Bao Liu, The Hasselt Diamond Workshop 2024 – SBDD XXVIII (28 Feb – 1 Mar 2024, Hasselt, Belgium). Diamond sensing of magnetic transitions and fluctuations of nanoparticles
- Ren-Bao Liu, Plenary talk, The 53rd Winter Colloquium on the Physics of Quantum Electronics (PQE-2024) (7 – 12 Jan 2024, Snowbird UT, USA). Quantum nonlinear spectroscopy and applications

(2) Professor Renbao Liu has organized, chaired, or served in committees of a number of international recognized conferences in the field, including

- *Member,* Program Committee, The 37th International Conference on the Physics of Semiconductors (16-21 Aug 2026, Tokyo, Japan)
- *Chair*, The Hong Kong Summit on Quantum Frontiers (15-18 Dec 2025, Hong Kong)
- *Advisory Committee Member,* The 33rd Annual International Laser Physics Workshop (30 Jun – 4 Jul 2025, Szeged, Hungary)
- *Program Chair,* 2025 IEEE International Conference on Quantum Control, Computing and Learning (IEEE qCCL2025) (25 – 28 June 2025, Hong Kong)
- *Chair*, the Xplorer Symposium on Quantum Sensing – Fundamentals, Functions, and Fun (1-5 Dec 2024, Hong Kong)
- *Advisory Committee Member*, The International Symposium on Quantum Computing and Quantum Optics 2024 (Hangzhou, Nov. 8-11, 2024)
- *Advisory Committee Member,* The 32nd Annual International Laser Physics Workshop (3-9 Jul 2024, São Paulo, Brazil)
- *Program Committee Member*, The 2nd International Conference on Emerging Quantum Technology (17-22 Sep 2023, Hefei)
- *Steering Committee Member,* The 31st Annual International Laser Physics Workshop (3-7 Jul 2023, online)

(3) Professor Lu Yang has been invited to serve on the Organizing Committee of the 35th International Conference on Diamond and Carbon Materials (2025).

7.3 Have any project team members taken leadership positions in editorial boards, scientific and professional organisations?

(1) Professor Renbao Liu has served as the Director of the State Key Laboratory of Quantum Information Technologies and Materials since 1 Jul 2025

(2) Professor Renbao Liu has served as the Director of Division 5 – Quantum Sensing and Quantum Metrology of the Greater Bay Area Quantum Science Center (Guangdong) since Oct 2023.

(3) Professor Renbao Liu has served in the Executive Editorial Board of Materials for Quantum Technology since 2020.

(4) Professor Lu Yang serves as Associate Editor for journal Materials Today since 2017 and sits on Editorial Board for journals such as National Science Review, Acta Mechanica Sinica, Science China Technological Sciences, International Journal of Extreme Manufacturing.

7.4 Any documentary proof of the application of technologies arising directly from this project?

N.A.

7.5 Other awards and recognitions as a result of this project (please specify):

(1) Professor Renbao Liu was elected a Fellow of American Physics Society in 2025.
(2) Professor Lu Yang is an elected fellow of Hong Kong Academy of Engineering (Young Member Section) in 2025.

8. Impacts

8.1 What are the current and expected impacts of the project on the long-term development of Hong Kong (social or economic development, e.g. patent, technology transfer, collaboration with external organisations, etc.)?

Expected impacts of this TRS project on the long-term development of Hong Kong include:

(1) The high-temperature ODMR platform and sensing protocols developed in this project is the only available quantum sensing approach to study magnetic nanomaterials working at high-temperatures (up to 1100 °C), which are well beyond other quantum sensing techniques and most conventional methods (which are yet limited by the low sensitivity and insufficient spatial resolution). With this technology, one can develop magnetic materials and devices particularly suitable for high-temperature environments such as magnetic sensors and control devices in engines and in space. This high-temperature sensing technology can also be applied to develop shape-memory magnetic materials which have applications in many scenarios including those for satellites in space. To project the IP of this technique, we have filed a patent application to the United States Patent and Trademark Office (No. 19/269,198). This technique has potential to develop into commercially available and profitable products with potential beneficiaries from auto industry, engine developers, and space technology.

(2) The AFM-ODMR quantum sensing platform and protocol are useful for studying thin-film magnetic materials under mechanical modulation. In the long term, this technique can lead to discovery of new magnetic materials with novel mechanical response and shape memory effects, of which the potential beneficiaries are developers of magnetic and mechanical sensors for, e.g., cars and touch screens. To project the IP of this technique, we have filed a patent application to the United States Patent and Trademark Office (No. 63/847,716).

(3) This project has led to a Ministry of Science and Technology of China 2030 project – the Quantum Science and Technology-National Science and Technology Major Project (2024-2028) and contributed to the establishment of the State Key Laboratory of Quantum Information Technologies and Materials. Such initiatives will enhance the bond between Hong Kong and mainland, add the values of the Hong Kong academic force to the R&D of China, and also contribute to bridge and the world. All such efforts in the long term will add to the foundation of the safety, stability, and prosperity of Hong Kong SAR as a part of China.

8.2 Others (please specify):

N.A.

9. Sustainability of the Project

9.1 Whether there are new ideas evolved directly from this project?

(1) Using the unique capability of the high-temperature quantum sensing platform to study in-situ the formation and re-orientation of nitrogen-vacancy centres in diamond under annealing conditions;

(2) Using the unique capability of the high-temperature quantum sensing platform to study the thermoremanent magnetism in nanoparticles which are relevant to the ancient magnetic history of planets and moons and to the heating-assisted magnetic storage;

(3) Using the unique capability of the high-temperature quantum sensing platform to study the interplay of structural and magnetic transitions in memory alloys;

(4) Using the unique capability of the AFM-ODMR platform to study mechanical tuned magnetic transitions in thin-film and 2D materials.

9.2 Whether there are new projects evolved directly from this project?

Ministry of Science and Technology of China 2030 project – **the Quantum Science and Technology-National Science and Technology Major Project** (Ref. 2023ZD0300600, 1 Jan 2024 – 31 Dec 2028, RMB18,000,000 allocated), "Study of critical nanomagnetism using diamond-based quantum sensing). PC: Renbao Liu; Co-PIs from the TRS project: Quan Li, Giulio Chiribella

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9.3 Whether there are new collaborations developed directly from this project?

We have established new collaborations with a materials scientists Professor Hou Yanglong in Peking University. After we had tested various samples from our team member's group (Professor Lu Jian's group in CityU) and the external collaborator (Professor Nie Yuefeng in Nanjing University), we realized that the Fe nano-flakes from Professor Hou's group are the most suitable test samples for our AFM-ODMR experiments. It turned out this new collaboration has led to fruitful results. A collaborative manuscript is under review in Science Advances.

We have also established new collaborations with the diamond sensing team in the Institute of Physics, the Chinese Academy of Sciences, which later led to the MOST 2030 project as a continuing project of this TRS project.

9.4 Please give details on how much money and from which sources has been obtained/requested for the specific purpose of continuing the work started under this project.

(1) RMB 18,000,000 is secured from the MOST 2030 project the Quantum Science and Technology-National Science and Technology Major Project (Ref. 2023ZD0300600, 1 Jan 2024 – 31 Dec 2028, RMB18,000,000 allocated), "Study of critical nanomagnetism using diamond-based quantum sensing).

(2) The State Key Laboratory of Quantum Information Technologies and Materials will allocate about HK$5,000,000 per year to continue the research started under this TRS project.

(3) The New Cornerstone Investigator (Professor Renbao Liu), with total annual allocation of RMB5,000,000, will allocate HK$1,000,000 to continue the research started under this TRS project.

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10. Statistics on Research Outputs

(Please ensure the statistics in this section are consistent with the information presented in other sections of this report.)

	Peer-reviewed journal publications	Conference papers	Scholarly, books, monographs and chapters	Patents awarded	Other research outputs (please specify)	
					Type	No.
No. of outputs arising directly from this research project	14 (Published: 8 Accepted: 2 Under review: 3 Under preparation: 1)	7	0	2		

11. Public Access of Completion Report

(PCs of projects funded in 2010/11 academic year or onwards are required to release the completion reports to the public through the RGC website. Completion reports containing information such as abstracts in non-technical terms, objectives, research output including the list of conference papers / publications / journals and research findings and contact information of PCs should be open to public access.)

Please specify the information, if any, that cannot be provided for public access and give the reasons.

Information that cannot be provided for public access	Reasons
N/A	

12. The Layman's Summary

(describe in layman's language the abstracts and research impact of the project.)

Quantum sensing uses quantum features of probes to enhance the performance of detection and metrology. Diamond quantum sensors, thanks to their superb quantum coherence under ambient conditions and the stability of the material in harsh, complicated environments (such as liquid, acid, and high temperatures), offer a broad range of applications such as nano-magnetometry, nano-thermometry, bio-sensing, mechanical sensing, and navigation. They also have the capability of simultaneously measuring multiple parameters. This project developed diamond-based multi-modal quantum sensing platforms including a setup combining nano-manipulation, nano-indentation, and nano-magnetometry and a setup that can perform quantum sensing at temperature as high as above 1100 °C. We applied the method to study the intrinsic magnetic properties of thin-film nano materials (a layer of iron with thinkness of a few nanometers and lateral size of a few microns). The study of magnetic nanomaterials is important to basic science (especially in condensed matter physics and materials science) and can lead to a broad range of applications (such as information storage, quantum memory, mechano-magnetic transducers, non-contact magnetic readout of thermal, structural, and mechanical properties of nanomaterials). The methods developed in this project can be employed to study interesting phenomena in other fields such as the ancient magnetic history of earth and moon and the shape memory and control of certain magnetic alloy materials (which are useful for space technology)