様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

令和　５ 年　 ６ 月　 ９ 日現在

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研究種目：基盤研究(A)（一般）
研究期間：2019～2022
課題番号：１９Ｈ００６６２

研究課題名（和文）ハイブリッド量子系における非線形現象

研究課題名（英文）Non-linear Phenomena in Hybrid Quantum Systems

研究代表者
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研究者番号：５０５９９５５３

交付決定額（研究期間全体）：（直接経費）　　34,700,000円

研究成果の概要（和文）：複数のスピン集団を環境と集団的に相互作用させたハイブリッド量子システムでは、ひとつの集団が基底状態に準備したもうひとつのスピン集団を励起させることができる。環境と集団的に相互作用するスピン集団のネットワークの中でおこるエネルギー（励起子）と相関輸送の両方を考察した。環境との集団的相互作用がもつ対称性を満たさない初期状態を準備することで、初期時刻に励起していなかったスピン集団を、単一スピンの減衰率よりもはるかに速い時間スケールで励起することができ、ネットワーク内でのエネルギー輸送が可能であることを示した。これをエンタングルメント精製にも拡張し、また、いくつかの実験的な実装の可能性を提案した。

研究成果の学術的意義や社会的意義
We have found new ways to transport quantum energy/correlations through a network on time scales much faster than what can be classical achieved. This provides the potential for new quantum thermodynamic based technologies including quantum batteries with significantly enhanced charging rates.

研究成果の概要（英文）：Hybrid quantum systems (HQS) composed of multiple spin ensembles collectively coupled to an environment allow one ensemble to drive the second one into its excited steady state even when that ensemble starts in its ground state. We have explored quantum energy / correlation transport through a network of ensembles collectively pairwise coupled to environments. When our initial state is not symmetric with respect to the collective reservoir couplings, different parts of the quantum wave function decay at different rates resulting in populations arising in initially unoccupied nodes on much faster timescales than the single spin damping rates. This allows the migration of energy across in the network. The same approach allows entanglement generation between ensembles not even coupled to the same reservoir. We proposed several potential experimental implementations for these phenomena. Further we also used our simulator to explore driven phenomena in arrays of superconducting qubits.

研究分野：Quantum Science and Technology

キーワード：Hybrid Quantum Systems　Quantum Phenomena　Quantum Thermodynamics　Quantum Simulation　Superradiance　Quantum Correlations　Quantum nonlinearity　Quantum Information

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９（共通）

１．研究開始当初の背景 (Back ground)

The 20th century saw the discovery of quantum mechanics, a set of principles describing physical reality at the atomic level of matter. Quantum physics allows a new paradigm for the processing of information where tasks can be performed that are either impossible in our classical world [1]. We have reached the stage where we have sufficient control over quantum systems so they can be used to perform interesting but predefined tasks with quantum advantage. The properties of such systems are defined by nature itself. Being able to design a system's fundamental properties will extend this advantage into entirely new regimes.

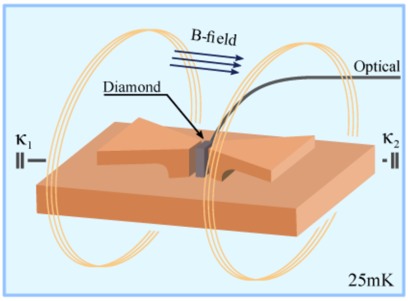

Fig1: A hybrid system consisting of lumped element resonator with diamond sample

Hybrid quantum systems [2] are seen as a way to design composite quantum systems with the properties one desires. In principle hybridization of distinct quantum systems allows us to exploit the best properties of these individual systems without their weaknesses or even design new properties. One well studied hybrid system is the superconducting circuits coupled to spin ensembles (Figure 1). Here strong coupling, memory storage and even sensing applications have been demonstrated [3,4,5]. However only recently have we reached the stage where the hybridization improves the composite systems overall properties. We have demonstrated how the coherent of the combined system was significantly longer than the individual components [6]. ***Going forward the fundamental question to be addressed is what unique phenomena can we explore in these hybrid systems (that are different to simple qubits systems) and what can these properties be used for?*** Current demonstrations have typically operated in the low excitation (linear) regime where the ensemble behaves like a simple harmonic oscillator. This has been sufficient to demonstrate quantum memory and sensing operations [4,5]. However, these spin ensembles are inherently nonlinear in nature and their potential needs to be explored.

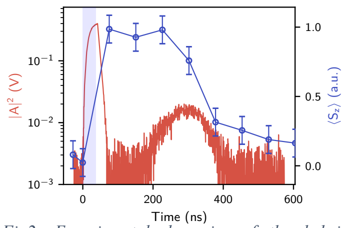

Fig2: Experimental dynamics of the hybrid system in super radiant configuration. Initially both the resonator (red curve) and ensemble (blue curve) are in their ground states [xx].

Nonlinear systems, whose outputs are not directly proportional to their inputs, are well known to exhibit many interesting, important and counter-intuitive phenomena. Such phenomena have profoundly changed our technological landscape [7]. ***Our ability to engineer new quantum metamaterials through hybridization has given us the ability to explore nonlinear effects in systems with no natural analog.*** This is the project's focus. Preliminary work involving superradiance (Fig 2) has already been demonstrated [8].

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[2] Z.-L Xiang, S. Ashhab, J.Q. You & F. Nori, Rev. Mod. Phys. 85, 623–653 (2013).
[3] X. Zhu et.al, Coherent coupling of a superconducting flux-qubit to an electron spin ensemble in diamond, Nature 478, 221-224 (2011).
[4] S. Saito et. al, Phys. Rev. Lett 111, 107008 (2013).
[5] H. Toida et. al, Electron paramagnetic resonance spectroscopy using a direct current-SQUID magnetometer directly coupled to an electron spin ensemble, Appl. Phys. Lett. 108, 052601 (2016).
[6] S. Putz et.al, Spectral Hole Burning in Microwave Photonics, Nature Photonics 11, 3639 (2016)
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[8] A. Angerer et.al, Superradiant Emission from Colour Centres in Diamond, Nature Physics 14,1168 (2018)

２．研究の目的 (Purpose of research)

Hybrid quantum systems are a relatively new area of physics exploration whose main focus has been for quantum computational applications including quantum transducers, multimode quantum memories etc. In most demonstrations, the ensemble has been operating in the weak excitation regime as an effective linear harmonic oscillator whose physical properties are well understood.

- Moving beyond this linear regime allows us to investigate nonlinear phenomenon in completely new and unexplored regimes - many with no classical correspondence due to the inherent quantum nature of the system. It is expected that such new phenomena will have many quantum technology-based applications.

Nonlinear effects have found many applications in our current technological world (switches etc). It is known that the principles of quantum mechanics will allow new and unexpected technological to be produced (especially for computational and communication tasks). Typically, quantum technologies have been based on quantum bits, rather than coherent ensembles of quantum bits. Our ability to design such hybrid quantum systems opens the possibility to:

- explore nonlinear phenomenon in a completely new and unexplored physical regimes of cQED, going well beyond the standard Dicke and Tavis–Cummings models.
- explore applications for ensemble-based hybrid quantum systems based on coherence and entanglement including the generation of nonclassical states of light and quantum batteries.

While this project is theoretical in nature, it will lead to the design of new experiments that are likely to be performed within Japan and internationally demonstrating novel nonlinear phenomena including for instance multistability, amplitude death, superradiance and super-absorption. Our theoretical models will show what forms of nonlinear behavior are realistically possible. We will show how these nonlinear phenomena can be utilized for both increasing our understanding of complex quantum phenomena in many body physics (strongly interacting systems and negative temperature effects for instance) as well as the development of new quantum technologies including quantum switches & batteries. Further we will explore how these hybrid systems may be used to generate various nonclassical states including spin-squeezed states, which are impossible to realize in a purely linear system. This would pave the way toward possible applications including the maser, quantum sensors and rapid charging quantum batteries.

３．研究の方法 (Research Methods)

This project is designed around the driven Tavis Cumming model in which we have a single ensemble of $N{\sim}10^3$ - 10^{12} spins coupled to a bosonic harmonic oscillator (superconducting resonator / Nambu-Goldstone boson mode for instance) in the weak, strong and ultra-strong regimes. Under ideal conditions this hybrid system should show bistability and superradiance behavior. It may also exhibit other nonlinear behavior (super absorption, amplitude death, multistablity etc). Several modelling techniques were used to investigate this nonlinear behavior and new quantum phenomena that arise.

- The first were simple Hamiltonian models that explored whether such behavior was possible and in what regimes it could occurs. It also enabled us to consider more than one ensemble coupled to the bosonic harmonic oscillator to determine what new nonlinear behavior may arise, especially as nonlocal correlations exist.
- Second was the development of a large-scale hybrid quantum systems simulator that explored both the temporal and steady state behavior of such systems under realistic conditions based on Markovian & non-Markovian master equations and quantum stochastic trajectory techniques. These systems were difficult to solve numerically due to N being extremely large (and other groups have made significant approximations). We however used a new technique to address this where we first determined the evolution of the mean field total spin population over time. Then we use rewrite our master equation in terms of an over-complete spin coherent state basis (which has better span with fewer elements) than the typical spin number basis. We then choose sufficient spin coherent basis states to only cover the regime of simulation being undertaken and dynamically vary it (according to the dynamics of the mean field total spin population) as the computation proceeds. This way we do not need to cover the entire spin range at once. The approach worked exceptionally well – especially in the double domain nuclear spin ensemble coupled to the Nambu-Goldstone boson mode case. This approach also allowed us to include inhomogeneous broadening, inhomogeneous coupling, finite coherence times, non-Marconian effects, the spatial distribution of spins with the superconducting circuit etc.
- The third intermediate to test the simulator are regimes far from the simple Hamiltonian models where a quantum stochastic trajectory approach for a smaller ensemble size is possible.

４．研究成果　(Research Achievements)

Let us detail our research achievements initially in chronological yearly order

Year 1: The first year of the project concentrated on two critical aspects:

- First was the development of a quantum simulator about to handle large number of qubits. The simulator included individual qubit thermalization and dephasing as well as collective relaxation. It was used to reproduce the experimental results observed in [Nature Physics 14,1168 (2018)] with good agreement. The simulator was then applied to model the dynamics of a double domain nuclear spin ensemble coupled to the Nambu-Goldstone boson in GaAs semiconductors. Our model predicted superradiance should be observable – quite a surprising result given the system.
- The second task undertaken was an exploration of nonlinear phenomena that potentially could be overserved in these hybrid quantum systems. We found that HQS with a collective drive exhibits highly nonlinear behavior that could be used simulate the properties of complex networks. Our simulator was able explore the dynamics of such systems.

Year 2: Beginning the second year of the project our simulation code was implemented on a 200 nodes cluster with 3 TB of RAM. This allowed larger scale simulation over longer time scales to be implemented.

Enhanced simulations of the dynamics of a double domain nuclear spin ensemble coupled to the Nambu-Goldstone boson were undertaken with realistic parameters (collective relaxation times shorter than individual spin dephasing times and then thermalization times). The RHS figure show the result of one of the simulations.

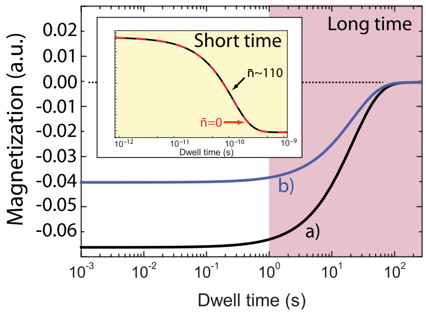

Figure 3: Plot of the total magnetization of the double domain nuclear spin vs the interaction (dwell) time

We showed both theoretically and experimental how collective and coher- ence effects arise in a double domain nuclear spin ensemble coupled to the Nambu-Goldstone boson in a GaAs semiconductor. The NG bosons long wavelength means both nuclear spin ensembles couple see the same mode. This leads to superradiant like decay event when our system is operating in the regime ($\hbar \omega_{\rm ns} \ll k_{\rm B} T$). Further it is likely that the short time dynamics will show entanglement between the two en- sembles. This work opens up the possibility for the exploration of novel collective behavior in solid state systems where the natural energies associated with those spins are much less than the thermal energy (this work was published in Phys. Rev. B 104, L121402 (2021)).

Next, we explored an open system quantum battery protocol using super radiance and absorption. This quantum-battery protocol using dark states to achieve both super extensive capacity and power density, with noninteracting spins coupled to a reservoir. Quantum correlations are essential for this to be achieved. Further, the power density scales with the number of spins N in the battery. While connected to the charger, the charged state of the battery is a steady state, stabilized through quantum interference in the open system. This work was published in Phys. Rev. Applied 13, 024092 (2020).

We also continued our exploration of HQS for quantum simulation. More specifically we use our simulator to explore discrete time crystals, a novel state of matter, emerging in periodically driven quantum systems (ensembles of qubits). Here, we introduced a method to describe, characterize, and explore the physical phenomena related to this phase of matter using tools from graph theory. The analysis of the graphs allows to visualizing time-crystalline order and to analyze features of the quantum system. For example, we explored in detail the melting process of a minimal model of a period-2 discrete time crystal and describe it in terms of the evolution of the associated graph structure. We showed that during the melting process, the network evolution exhibits an emergent preferential attachment mechanism, directly associated with the existence of scale-free as seen in Fig 4. This work was published in Sci. Adv. 6, eaay8892 (2020).

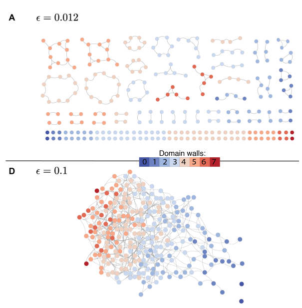

Figure 4: Graph of the network from the melting time crystal

Year 3: In the third year of the project our primary focus was on the exploration of multiple ensembles coupled to single/multiple baths to determine whether superradiance / superabsorption can enhance energy transport through a network in a truly quantum regime. The transfer of energy through a network of nodes is fundamental to how both nature and current technology operate. Traditionally, we think of the nodes in a network being coupled to channels that connect them, in which energy is passed from node to channel to node until it reaches its targeted site. Here we introduce an alternate approach to this, where our channels are replaced by collective environments which interact with pairs of nodes. We show how energy initially located at a specific node can arrive at a target node—even though that environment may be at zero temperature. Energy is not flowing from node to node. Instead, our initial state is not symmetric with respect to the collective coupling to the reservoirs and so different parts of the quantum wave function decay at different rates (or not at all). This results in populations arising in nodes which were initially unoccupied. Combining this behavior with superradiant decay and absorption, we show the apparent flow of energy from node to node in the network (Fig 5). Further, we show that such a migration occurs on much faster timescales than the damping rate associated with a single spin coupled to the reservoir. Our approach shows the power of being able to tailor both the system and environment and the symmetries associated with them to provide new directions for future quantum technologies. This work was published in Phys. Rev. B 104, L140303 (2021).

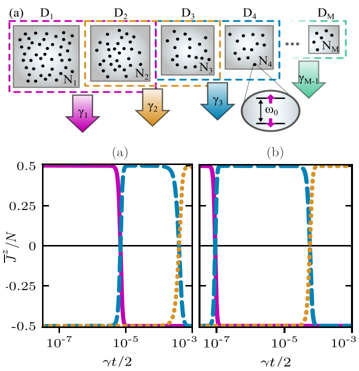

Figure 5: Illustration of a dissipatively coupled chain of spin domains

The second focus on the project this year was the exploration of driven HQS to understand their potential for quantum simulation tasks. Here we showed a scheme to perform universal simulation in the low frequency regime using a quantum system with one-dimensional nearest-neighbor coupling that are commonly available in the NISQ era HQS's. Computational problems are encoded in the effective Hamiltonian of the quantum systems under the effect of external driving. We illustrated how the computation works through two examples from NP complete problems and quantum chemistry simulation. This work was published in Phys. Rev. B 105, 075140 (2022).

Finally, we also wrote a perspective article for Applied Physics Letters [Applied Physics Letters 119, 110501 (2021)] where we detailed the importance of rigorous establishing the presence of entanglement in HQS composed of several spin ensembles and presented an approach for achieving this. Fundamentally, it would demonstrate that a single qubit state could be stored and retrieved from a macroscopic ensemble with of more than a trillion spins. It would further show that two diamonds, two macroscopic object, can be entangled over centimeter distance. This shall enhance the understanding of entanglement manipulation for macroscopic objects.

Year 4:

In the last year of the project our primary focus was to explore whether quantum correlations can be transported via this HQS nonlinear effects (Fig 6). We have shown that by utilising reservoir engineering, and with a completely separable initial state, entanglement can be generated between two spins which are not coupled to each other or even coupled to the same reservoir. We had focused mostly here on the case where the two spins collectively decay into different reservoirs with a single common spin domain collectively decaying into both reservoirs. For this case, the entanglement is maximised for a large number of spins in the central domain. The speed of entanglement generation is also maximised for a larger spin population in the central domain and shows a super radiant like enhancement. This in principle allows on to overcome the effects of dephasing present in each of the individual ensembles. Further entanglement generation via this mechanism is not limited to the three spin-domain case, but can also occur between qubits in the outer domains of four and five domain systems as well. This work was submitted to publication to Physical Review A in late March 2023.

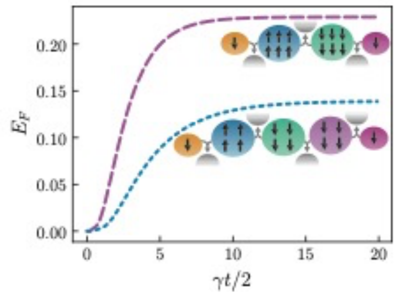

Figure 6: Entanglement transport

Research Output: Over the entire project 11 papers were published including 1 Science Advances, 2 Physical Review Letters and 2 Physical Review B Letters. Further 1 keynote, 11 invited and 13 contributed talks were given at international conferences. Finally, a book chapter entitled "Collective Effects in Hybrid Quantum Systems" was published in 2022 in the Springer Quantum Science and Technology series book **Hybrid Quantum Systems** whose editors were Y. Hirayama, K. Ishibashi and K. Nemoto.

５．主な発表論文等

〔雑誌論文〕　計12件（うち査読付論文　12件／うち国際共著　8件／うちオープンアクセス　3件）

１．著者名 Sakurai A.、Bastidas V. M.、Munro W. J.、Nemoto Kae	４．巻 126
２．論文標題 Chimera Time-Crystalline Order in Quantum Spin Networks	５．発行年 2021年
３．雑誌名 Physical Review Letters	６．最初と最後の頁 120606 (1-6)
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevLett.126.120606	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 -

１．著者名 Bastidas V. M.、Estarellas M. P.、Osada T.、Nemoto Kae、Munro W. J.	４．巻 102
２．論文標題 Quantum metamorphism	５．発行年 2020年
３．雑誌名 Physical Review B	６．最初と最後の頁 224307 (1-10)
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevB.102.224307	査読の有無 有
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１．著者名 Zha Chen、Bastidas V.M.、Gong Ming、Wu Yulin、Rong Hao、Yang Rui、Ye Yangsen、Li Shaowei、Zhu Qingling、Wang Shiyu、Zhao Youwei、Liang Futian、Lin Jin、Xu Yu、Peng Cheng-Zhi、Schmiedmayer J.、Nemoto Kae、Deng Hui、Munro W.J.、Zhu Xiaobo、Pan Jian-Wei	４．巻 125
２．論文標題 Ergodic-Localized Junctions in a Periodically Driven Spin Chain	５．発行年 2020年
３．雑誌名 Physical Review Letters	６．最初と最後の頁 170503 (1-6)
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevLett.125.170503	査読の有無 有
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１．著者名 Estarellas M. P.、Osada T.、Bastidas V. M.、Renoust B.、Sanaka K.、Munro W. J.、Nemoto K.	４．巻 6
２．論文標題 Simulating complex quantum networks with time crystals	５．発行年 2020年
３．雑誌名 Science Advances	６．最初と最後の頁 aay8892 (1-8)
掲載論文のDOI（デジタルオブジェクト識別子） 10.1126/sciadv.aay8892	査読の有無 有
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1．著者名 Quach James Q.、Munro William J.	4．巻 14
2．論文標題 Using Dark States to Charge and Stabilize Open Quantum Batteries	5．発行年 2020年
3．雑誌名 Physical Review Applied	6．最初と最後の頁 024092 (1-9)
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevApplied.14.024092	査読の有無 有
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1．著者名 Waechtler C. W.、Bastidas V. M.、Schaller G.、Munro W. J.	4．巻 102
2．論文標題 Dissipative nonequilibrium synchronization of topological edge states via self-oscillation	5．発行年 2020年
3．雑誌名 Physical Review B	6．最初と最後の頁 014309 (1-9)
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevB.102.014309	査読の有無 有
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1．著者名 Michael Hanks, William J. Munro, and Kae Nemoto	4．巻 1
2．論文標題 Decoding Quantum Error Correction Codes With Local Variation	5．発行年 2020年
3．雑誌名 IEEE Transactions on Quantum Engineering	6．最初と最後の頁 4500408(1-8)
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TQE.2020.2967890	査読の有無 有
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1．著者名 Bastidas V. M.、Haug T.、Gravel C.、Kwek L.-C.、Munro W. J.、Nemoto Kae	4．巻 105
2．論文標題 Stroboscopic Hamiltonian engineering in the low-frequency regime with a one-dimensional quantum processor	5．発行年 2022年
3．雑誌名 Physical Review B	6．最初と最後の頁 075140(1-13)
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevB.105.075140	査読の有無 有
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１．著者名 Dias Josephine、Wachtler Christopher W.、Bastidas Victor M.、Nemoto Kae、Munro William J.	４．巻 104
２．論文標題 Reservoir-assisted energy migration through multiple spin domains	５．発行年 2021年
３．雑誌名 Physical Review B	６．最初と最後の頁 L140303(1-6)
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevB.104.L140303	査読の有無 有
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１．著者名 Mao Yingqiu、Gong Ming、Nemoto Kae、Munro William J.、Majer Johannes	４．巻 119
２．論文標題 Perspective on witnessing entanglement in hybrid quantum systems	５．発行年 2021年
３．雑誌名 Applied Physics Letters	６．最初と最後の頁 110501(1-7)
掲載論文のDOI（デジタルオブジェクト識別子） 10.1063/5.0062842	査読の有無 有
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１．著者名 Fauzi M. H.、Munro William J.、Nemoto Kae、Hirayama Y.	４．巻 104
２．論文標題 Double nuclear spin relaxation in hybrid quantum Hall systems	５．発行年 2021年
３．雑誌名 Physical Review B	６．最初と最後の頁 L121402(1-6)
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevB.104.L121402	査読の有無 有
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１．著者名 Sakurai Akitada、Bastidas Victor M.、Estarellas Marta P.、Munro William J.、Nemoto Kae	４．巻 104
２．論文標題 Dephasing-induced growth of discrete time-crystalline order in spin networks	５．発行年 2021年
３．雑誌名 Physical Review B	６．最初と最後の頁 054304(1-9)
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevB.104.054304	査読の有無 有
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〔学会発表〕　計25件（うち招待講演　12件／うち国際学会　23件）

1．発表者名 V. M. Bastidas, Chen Zha, Ming Gong, Yulin Wu, Hao Rong, Rui Yang, Yangsen Ye, Shaowei Li, Qingling Zhu, Shiyu Wang, Youwei Zhao, Futian Liang, Jin Lin, Yu Xu, Cheng-Zhi Peng, Jorg Schmiedmayer, Kae Nemoto, Hui Deng, W. J. Munro, Xiaobo Zhu and Jian-Wei Pan	
2．発表標題 Quantum simulation with periodically-driven superconducting quantum processors	
3．学会等名 The symposium on Quantum Computing: Status and Outlook at the 68th JSAP Meeting 2021, Online conference, Japan, March 16-19 (2021)（招待講演）	
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2．出版社	**5．総ページ数**
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〔産業財産権〕

〔その他〕

－

6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
研究分担者	根本　香絵 (Nemoto Kae) (80370104)	沖縄科学技術大学院大学・量子情報科学・技術ユニット・教授 (38005)	

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関			
ドイツ	Max Planck Institute			
オーストラリア	University of Adelaide			
米国	University of California Berkeley			

共同研究相手国	相手方研究機関			
シンガポール	National University of Singapore	Nanyang Technological University		
中国	Univ. of Science and Technology of China			