International Symposium on

Dynamics in Artificial Quantum Systems

January 12-14, 2016, Tokyo

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Presentation abstracts

Talks	Tu01	~	Tu10
	We01	~	We10
	Th01	~	Th10
Posters	P01	~	P53

Venue:
Research Center for Advanced Science and Technology
The University of Tokyo, Komaba Research Campus

Organizers: Yasunobu Nakamura, Seigo Tarucha, Koji Ishibashi
Co-organized by JSPS KAKENHI

DAQS2016 Time Table

	Jan 12 (Tue)	Jan 13 (Wed)	Jan 14 (Thu)
8:30-9:30	Registration&Opening		
9:30-10:00	Tobar	Munro	Shindo
10:00-10:30	Teufel	Longdell	Du
10:30-11:00	Coffee break	Coffee break	Coffee break
11:00-11:30	Loss	Blais	Ueda
11:30-12:00	Deacon	Tsai	Home
12:00-12:30	Kuemmeth	Jiang	Fukuhara
12:30-14:00	Lunch	Lunch	Lunch
14:00-14:30	Sandoghdar	De Franceschi	Rauschenbeutel
14:30-15:00	Usami	Ota	Aoki
15:00-15:30	Lutz	Yamamoto	Nori
15:30-16:00	Coffee break	Photo+Coffee break	Coffee break
16:00-16:30	Poster session	Poster session	Schuster
16:30-17:00			Siddiqi
17:00-17:30			Closing&Departure
17:30-18:00	Furusawa	Kono	
18:00-18:30	Taylor	Fraser	
18:30-20:30		Banquet	

Poster Session (All the posters can be posted throughout the symposium.)

Jan 12 (Tue) 16:00-17:30

Poster No.	Name	Affiliation	Poster Title
P01	Allison, Giles Daniel	RIKEN, CEMS	Hybrid cQED architecture as a model system for non-equilibrium physics in condensed matter
P03	Billangeon, Pierre	The University of Tokyo, Research Center for Advanced Science and Technology (RCAST)	Circuit-QED-based quantum architectures relying on longitudinal interactions
P05	Cirio, Mauro	RIKEN, iTHES	Ground state electroluminescence
P07	Dooley, Shane	National Institute of Informatics	Spin squeezing via interaction with a dissipative qubit
P09	Geng, Jianpei	University of Science and Technology of China	Experimental fault-tolerant universal quantum gates with solid-state spins under ambient conditions
P11	Goto, Hayato	Toshiba Corporation, Corporate Research & Development Center	Adiabatic quantum computation using a quantum-mechanical bifurcation of a nonlinear oscillator network
P13	Hatakeyama, Ryoko	The University of Tokyo, Department of Physics	Analysis of motion of minute quantum machines
P15	Hsu, Chen-Hsuan	RIKEN, CEMS	Anti-ferromagnetic nuclear spin helix and topological superconductivity in ^{13}C nanotubes
P17	Inomata, Kunihiro	RIKEN, CEMS	Single microwave-photon detector using an impedance-matched Λ system
P19	Ishikawa, Toyofumi	The University of Tokyo, Research Center for Advanced Science and Technology (RCAST)	Time-bin photon generation using superconducting circuits
P21	Kawasaki, Kento	The University of Tokyo, Department of Applied Physics	Bayesian estimation of nuclear-spin bath for adaptive feedback with a single-electron spin qubit
P23	Kono, Shingo	The University of Tokyo, Research Center for Advanced Science and Technology (RCAST)	Quantum non-demolition detection of an itinerant single photon using a superconducting qubit
P25	Lambert, Neill	Tsinghua University, Institute of Microelectronics & RIKEN CEMS	Bistable photon emission in hybrid-QED
P27	Li, Zhou	RIKEN, iTHES	Interplay of chiral anomaly and particle hole asymmetry on the magneto-optical conductivity of Weyl semimetals
P29	Nakajima, Takashi	RIKEN, CEMS	Controlling entanglement of spin qubits in a triple quantum dot
P31	Nakamura, Satoshi	Toshiba Corporation, Corporate Research & Development Center	Toward frequency-domain quantum computation using a monolithic cavity of rare-earth-ion-doped crystal
P33	Noguchi, Atsushi	The University of Tokyo, Research Center for Advanced Science and Technology (RCAST)	Electromechanical system using a Si3N4 membrane inside a 3D microwave cavity
P35	Ochiai, Tetsuyuki	National Institute for Materials Science, Photonic Materials Unit	Nobel phenomena of photons in three-dimensional ring-resonator arrays
P37	Otsuka, Tomohiro	RIKEN, CEMS	Electron spin resonance in a quadruple quantum dot
P39	Qin, Wei	RIKEN, CEMS	Controllable single-photon transport between remote coupled-cavity arrays
P41	Takeda, Kenta	RIKEN, CEMS	A fast addressable spin qubit in a silicon quantum dot
P43	Toida, Hiraku	NTT Basic Research Laboratories	Electron paramagnetic resonance spectroscopy using a micrometer-sized dc-SQUID magnetometer directly coupled to an electron spin ensemble
P45	Tsunoda, Takahiro	The University of Tokyo, Research Center for Advanced Science and Technology (RCAST)	Randomized benchmarking on superconducting qubit and gate fidelity improvement
P47	Wang, Xin	Xi'an Jiaotong University	Tunable electromagnetically induced transparency in a composite superconducting system
P49	Xu, Xiangkun	University of Science and Technology of China	Experimental observing non-Markovianity of quantum evolution with entanglement in solid state system
P51	Yang, Guang	RIKEN, CEMS	Long-distance entanglement of spin qubits via quantum Hall edge states
P53	Tajima, Hiroyasu	RIKEN, CEMS	Measurement-based Formulation of Quantum Heat Engine and Optimal Efficiency with Finite-Size Heat Baths

Poster Session (All the posters can be posted throughout the symposium.)

Jan 13 (Wed) 16:00-17:30

Poster No.	Name	Affiliation	Poster Title
P02	Ashida, Yuto	The University of Tokyo, Department of Physics	Multi-particle quantum dynamics under continuous observation
P04	Chong, Yonuk	Korea Research Institute of Standards and Science, Center for Quantum Measurement	Measurement of gate fidelity in a superconducting 3D transmon qubit
P06	Devitt, Simon	RIKEN, CEMS	Mobile quantum cryptography with a quantum sneakernet
P08	Frisk Kockum, Anton	RIKEN, CEMS	Quantum optics with giant artificial atoms
P10	Giavaras, Giorgos	RIKEN, CEMS	ac-spectroscopy of spin-orbit coupled spins in double quantum dots
P12	Hamazaki, Ryusuke	The University of Tokyo, Department of Physics	Generalized Gibbs ensemble in nonintegrable systems with an extensive number of local symmetries
P14	Hisatomi, Ryusuke	The University of Tokyo, Research Center for Advanced Science and Technology (RCAST)	Bidirectional conversion between microwave and light via ferromagnetic magnons
P16	Ikegami, Hiroki	RIKEN, CEMS	Topological aspects of superfluid ^{3}He detected by electrons at surface
P18	Ishibashi, Kenta	Meiji University	Synchronization of van der Pol oscillators in the quantum regime
P20	Kakuyanagi, Kosuke	NTT Basic Research Laboratories	Visibility enhancement by a quantum multi readout
P22	Kondo, Yasushi	Kinki University	NMR system for studying phase decoherence
P24	Koshino, Kazuki	Tokyo Medical & Dental University	Theory of microwave single-photon detection using an impedance-matched Lambda system
P26	Li, Tiefu	Tsinghua University, Institute of Microelectronics	Cavity QED with ferromagnetic magnons in a small YIG sphere
P28	Lin, Zhirong	RIKEN, CEMS	Josephson parametric amplifier and oscillator and their application to quantum information processing
P30	Nakamura, Ippei	RIKEN, CEMS	Single-ion spectroscopy of rare-earth ions contained in an inorganic crystal at cryogenic temperature
P32	Nasyedkin, Kostyantyn	RIKEN, CEMS	Dynamics of surface state electrons on liquid helium exposed to microwave intersubband excitation and quantizing magnetic field
P34	Noiri, Akito	The University of Tokyo, Department of Applied Physics	Coherent electron-spin-resonance control of three individual spins in a triple quantum dot
P36	Osada, Alto	The University of Tokyo, Research Center for Advanced Science and Technology (RCAST)	Cavity optomagnonics using a whispering gallery mode resonator
P38	Park, Jin-Hong	RIKEN, CEMS	Fractional charge in quantum dot arrays with density modulation
P40	Tabuchi, Yutaka	The University of Tokyo, Research Center for Advanced Science and Technology (RCAST)	Coherent coupling between ferromagnetic magnon and a superconducting qubit
P42	Thanh Phuc, Nguyen	RIKEN, CEMS	Controlling and probing non-Abelian emergent gauge potentials in spinor Bose-Fermi mixtures
P44	Tokunaga, Yuuki	NTT Secure Platform Laboratories	Photonic quantum gates using multilevel atomic systems
P46	Wang, Rui	RIKEN, Advanced Device Laboratory	Spin orbit interaction in single Ge/Si core/shell nanowires with electrically swinging dual gates
P48	Wataura, Hikaru	Univ. of Tsukuba, Pure and Applied Sciences	Quantum computation using spin-vortex induced loop currents as qubits
P50	Yamazaki, Rekishu	The University of Tokyo, Research Center for Advanced Science and Technology (RCAST)	Opto-electromechanics for quantum transducer
P52	Zhang, Peng	RIKEN, CEMS	Coherent manipulation of a Majorana qubit by a mechanical resonator
P54	Jing, Hui	RIKEN, CEMS	Parity-time-broken optomechanics

High-Q and Novel Cavity Structures for Photon-Spin Strong Coupling and Acoustic Wave Readout at the Quantum Limit

M.E. Tobar[1], J. Bourhill[1], N Kostylev[1], M Goryachev[1], D Creedon[1], E.N, Ivanov[1], S. Galliou

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Strong coupling between microwave photons and spins at millikelvin temperatures is necessary to realise quantum information processing. We will present our most recent results in coupling strongly to a variety of cavity and spin systems. Novel cavity systems include whispering gallery modes, 3D lumped element meta-structures based on the reentrant cavity and dielectric TE modes. Spin systems include paramagnetic iron group and rare-earth impurities doped in low-loss crystalline materials, P1 centers in diamond and magnons in ferrimagnetic YIG.

In particular we will focus on new cavities, which couple photons and magnons in YIG spheres in a super- and ultra-strong way at around 20 mK in temperature. Few/Single photon couplings (or normal mode splitting, $2g$) of more than 7 GHz at microwave frequencies are obtained for a 15.5 GHz mode. Types of cavities include multiple post reentrant cavities, which co-couple photons at different frequencies with a coupling greater that the free spectral range, as well as spherical loaded dielectric cavity resonators. In such cavities we show that the bare dielectric properties can be obtained by polarizing all ferromagnetic effects and magnon spin wave modes to high energy using a 7 Tesla magnet. We also show that at zero-field, collective effects of the spins significantly perturb the photon modes. Other effects like time-reversal symmetry breaking are observed.

Finally, experiments at the University of Western Australia with the goal to read out electromechanical systems in the ground state will also be mentioned. The first is using quartz BAW resonators, which have the highest $Q \times f$ product of any acoustic system by a few orders of magnitude, with the acoustic motion detected through the piezo-electric effect. The second is through a high-Q acoustic sapphire dumbbell coupled parametrically through high-Q whispering gallery modes due to the strain dependent permittivity. Such systems can be use as precise tests of fundamental physics.

Squeezed Light and Motion in Microwave Optomechanical Circuits

John Teufel

National Institute of Standards and Technology

In optomechanical circuits, radiation pressure forces offer the ability to engineer strong interactions between photonic and phononic degrees of freedom. In this talk, I will describe two recent experiments which explore the role of squeezed states and quantum nondemolition (QND) measurements in either microwave light fields or mechanical motion. First, we demonstrate how radiation pressure shot noise can be suppressed by interrogating a micromechanical resonator with displaced squeezed states of the microwave field. We further show how the fundamental optomechanical interaction reciprocally allows the mechanical system to perform a QND measurement of the amplitude quadrature of the microwave light field. In a second experiment, we demonstrate that a coherent pair of microwave pumps can sideband cool a mechanical resonator into a squeezed steady state of motion. We verify the squeezed and antisqueezed mechanical quadrature fluctuations with an independent, continuous, QND measurement from second pair of coherent microwave pumps. Together these experiments demonstrate the utility of optomechanical systems for engineering nonclassical states, quantum-enhanced sensing and quantum measurement.

From Majorana- to Para-Fermions in Nanowires and Atomic Chains

Daniel Loss

Department of Physics, University of Basel, Switzerland and

RIKEN Center for Emergent Matter Science, Wako, Saitama, Japan

I will present recent theoretical results on exotic quantum bound states which can emerge in one and two dimensions in the presence of spin orbit interaction or spatially periodic magnetic fields [1], in RKKY systems forming intrinsic spin helices [2], with and without superconductivity. I will present candidate materials such as semiconducting Rashba nanowires, ^{13}C nanotubes [3], and atomic magnetic chains [2]. Examples of such bound states are fractionally charged fermions, Majorana fermions, and, in particular, parafermions [4] whose braiding statistics enables entanglement (in contrast to Majoranas) [5]. I will mention recent progress on error correction for topological quantum computation.

[1] J. Klinovaja, P. Stano, and D. Loss, PRL 109, 236801 (2012).
[2] J. Klinovaja, P. Stano, A. Yazdani, and D. Loss, PRL 111, 186805 (2013).
[3] C. Hsu, P. Stano, J. Klinovaja, and D. Loss, arXiv:1509.01685.
[4] J. Klinovaja and D. Loss, PRL 112, 246403 (2014); PRB 90, 045118 (2014).
[5] A. Hutter and D. Loss, arXiv:1511.02704.

Gapless Andreev Bound States in HgTe topological Josephson junctions

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A topological insulator in proximity with a superconductor is predicted to give rise to unconventional induced *p*-wave superconductivity. In a topological insulator Josephson junction this results in a doublet of topologically protected gapless Andreev bound states with energies which vary 4π-periodically with the superconducting phase difference across the junction. In practice the detection of a 4πphase relation is complicated due to the coexistence of gapped conventional modes, parallel bulk conductance and various relaxation mechanisms which restore a 2πperiodicity. The 4πJosephson effect can therefore only be unveiled by studying the dynamics of the junction on short timescales. We will report the observation of an anomalous response to rf irradiation in Josephson junctions with weak links comprised of the well characteried topological insulators based on HgTe (both 3D and 2D). We observe the suppression of odd Shapiro step(s) indicating a 4π-periodic contribution to the supercurrent with amplitude compatible with the expected contribution of a gapless Andreev doublet.

Symmetric operation and nuclear notch filtering in GaAs double quantum dots

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Spin qubits based on few-electron semiconducting quantum dots are promising candidates for quantum computation, due to their potential for miniaturization, scalability and fault tolerance. In this talk I will present recent results on how to mitigate electrical and nuclear noise in GaAs singlet-triplet qubits.

The traditional way of implementing spin exchange rotations involves detuning the qubit away from the symmetric (1,1) charge configuration, thereby temporarily hybridizing with the (0,2) charge state. Due to the large dipole coupling the resulting exchange oscillation suffers from detuning noise, motivating operation at sweet spots[1] or in the multi-electron regime[2]. Alternatively, exchange rotations can be implemented by symmetrically lowering the middle barrier. This method yields less relative exchange noise, significantly enhanced free induction decay times, and quality factors comparable to those reported in silicon quantum dot devices using similar techniques[3].

In order to decouple the singlet-triplet qubit from nuclear spin fluctuations, we investigate Carr-Purcell-Meiboom-Gill (CPMG) sequences in more detail. At high magnetic fields we find that qubit dephasing is limited by narrow-band high-frequency noise arising from Larmor precession of ^{69}Ga, ^{71}Ga, ^{75}As nuclear spins, similar to what has been observed at intermediate magnetic field[4]. By aligning the notches of the CPMG filter function with differences of the discrete nuclear Larmor frequencies we demonstrate a qubit coherence time of 0.87 ms, i.e. more than five orders of magnitude longer than the duration of a π exchange gate in the same device.

[1] O. E. Dial et al. Physical Review Letters 110, 146804 (2013).
[2] A. P. Higginbotham et al, Phys Rev Lett 112, 026801 (2014).
[3] M. D. Reed et al, arXiv:1508.01223 (2015).
[4] H. Bluhm et al. Nature Physics 7, 109 (2011).

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Single Rare Earth Ions as a New Platform for Solid-State Quantum Optics

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Friedrich Alexander University (FAU), Erlangen, Germany

In the first part of this talk, I present an overview of our experimental work on the efficient interaction of light and single organic molecules at cryogenic temperatures in the near field [1] or through strong focusing [2, 3]. Furthermore, I shall report on the direct long-distance communication of two quantum emitters, where single photons are funneled in and out of molecules using lenses of high numerical aperture [4]. We will see that the key concept for efficient photon-atom interaction is mode matching and that a single atom can block a propagating light beam by up to 100% [5]. We will also examine the efficient coherent coupling of single molecules to a dielectric nanoguide [6].

To get around some of the limitations of organic molecules, such as lack of spin in the ground state, we have recently explored rare earth ions in solid crystals. We showed the first high-resolution spectroscopy and manipulation of single Pr^{3+} ions in an yttrium orthosilicate (Pr:YSO) crystal environment [7, 8]. The special feature of this system is access to the hyperfine splitting caused by the interaction of the 4f electrons and the nucleus, leading to sets of sublevels with exceptionally long coherence times at cryogenic temperatures, on the order of minutes and hours. This ground state splitting can serve as a lambda level scheme, a key ingredient for many prospective applications in quantum optics, in particular for qubit storage and manipulation.

In our first experiments, we demonstrated state initialization via an optical pulse sequence. Continuing from there we target direct coherent spin manipulation in the electronic ground and excited state via radio frequencies. Moreover, we discuss future challenges in reducing spectral diffusion and line broadening down to the expected natural linewidth, combination with microcavities or plasmonic nano-antennas to enhance the photon yield, and schemes for on-chip integration.

References:

[1] I. Gerhardt, et al., *Phys. Rev. Lett*. 98, 033601 (2007).
[2] G. Wrigge, et al., *Nature Physics* 4, 60 (2008).
[3] M. Pototschnig, et al. *Phys. Rev. Lett.* **107**, 063001 (2011).
[4] Y. Rezus, et al., *Phys. Rev. Lett*. **108**, 093601 (2012).
[5] G. Zumofen, et al., *Phys. Rev. Lett.* **101**, 180404 (2008).
[6] S. Faez, et al., *Phys. Rev. Lett.* 113, 213601 (2014).
[7] T. Utikal, et al. , *Nature Communications* **5**, 3627 (2014).
[8] E. Eichhammer, et al., *New J. Physics* **17**, 083018 (2015).

Quantum magnonics with light

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Building artificial many-body quantum systems, such as quantum computers, quantum communication networks, and quantum simulators, emerges as the frontier in scientific endeavor. A canonical well-controlled quantum system is based on cavity quantum electrodynamics, where an atom placed in a cavity interacts with photons in a well-engineered cavity mode. We have recently demonstrated that the atom and the cavity photons can be replaced with a superconducting qubit and ferromagnetic magnons, respectively, and opened the field of "quantum magnonics" [1]. On the one hand, the quantum magnonics links the well-developed quantum coherent control to the blooming field of spintronics. The unique properties of the ferromagnetic magnons, on the other hand, offer new possibilities in the field of quantum electronics.

To further expand the potential of the quantum magnonics we are investigating how the magnons interact with optical photons in the setting compatible with quantum electronics. Here we report our recent activities on quantum magnonics with light. In particular presented is the experiment in which the coherent and bidirectional conversions between microwave and optical photons via ferromagnetic magnons is realized. We also present the result of cavity opto-magnonics [2], where magnons in a spherical ferromagnetic crystal interact with photons in a whispering gallery mode supported by the same crystal.

[1] Y. Tabuchi, S. Ishino, T. Ishikawa, A. Noguchi, R. Yamazaki, K. Usami, and Y. Nakamura, Science **349,** 405 (2015).

[2] A. Osada, R. Hisatomi, A. Noguchi, Y. Tabuchi, R. Yamazaki, K. Usami, M. Sadgrove, R. Yalla, M. Nomura, and Y. Nakamura, arXiv:1510.01837.

Tu08

Modification of phonon processes in nano-structured rare-earth-ion-doped materials

Thomas Lutz[1], Lucile Veissier[1], Charles Thiel[2], Rufus Cone[2], Paul Barclay[1], Wolfgang Tittel[1]

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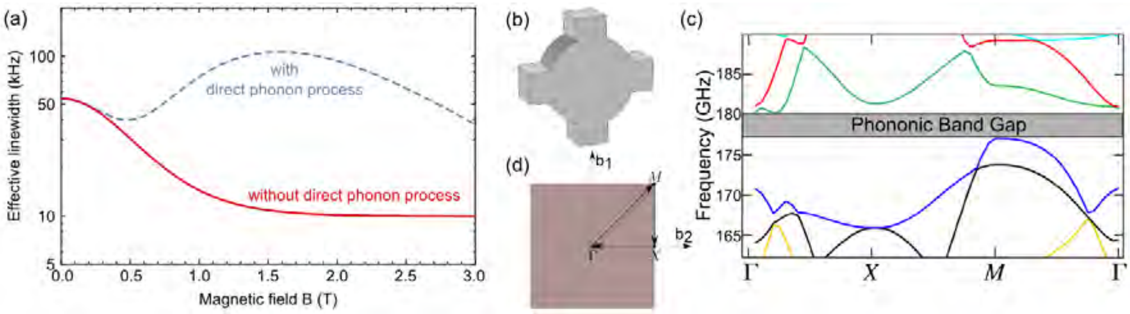
Nano-structuring impurity-doped crystals affects the phonon density of states and thereby modifies the atomic dynamics induced by interaction with phonons. We propose the use of nanostructured materials in the form of powders or phononic bandgap crystals to enable or improve persistent spectral hole-burning and coherence for inhomogeneously broadened absorption lines in rare-earth-ion-doped crystals[1]. This is crucial for applications such as ultra-precise radio-frequency spectrum analyzers and optical quantum memories.

First, as an example, we discuss how phonon engineering can enable spectral hole-burning and reduce homogeneous linewidths in erbium-doped materials operating in the convenient telecommunication band, and present simulations for density of states of nano-sized powders and phononic crystals for the case of Y2SiO5, a widely-used material in current quantum memory research. In the figure below, the effect of phonon restriction on the homogeneous linewidth (a) together with the geometry of the phononic crystal (b) and its bandstructure (c) are shown for a typical, erbium doped material. Panel (d) of the Figure shows the points of the reciprocal lattice of the phononic crystal traversed in the band structure.



Second, we will report on experimental investigation towards the realization of impurity-doped nanocrystals with good spectroscopic properties. Crystal properties such as nuclear spin lifetime are strongly affected by mechanical treatment, and spectral hole-burning can serve as a sensitive method to characterize the quality of REI doped powders. Different methods for obtaining powders are compared and the influence of annealing on the spectroscopic quality of powders is investigated. We conclude that annealing can reverse some detrimental effects of powder fabrication and, in certain cases, the properties of the bulk material can be reached. Such nano-sized particles can be used to show the suppression of detrimental phonons.

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1 Thomas Lutz et. al, arXiv 1504.02471

Hybrid Quantum Information Processing

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We are working on hybrid quantum information processing, which combines two methodologies of quantum information processing – qubits and continuous variables (CVs). More precisely, we encode quantum information onto single-photon-based qubits and utilize CV quantum processors to realize universal optical quantum computing. The advantage of this methodology is that we can have both high-fidelity nature of qubits and determinisity of CV quantum processors. In other words, we can enjoy both particle- and wave-nature of quantum mechanics. Towards this goal we performed various things, which include quantum error correction with nine-party CV entanglement [1], teleportation of Schrödinger's cat state [2], adaptive homodyne measurement with phase-squeezed states [3], deterministic teleportation of time-bin qubits [4], creation of ultra-large-scale CV cluster states [5], and generation and measurement of CV entanglement on a chip [6].

References

[1] T. Aoki, G. Takahashi, T. Kajiya, J. Yoshikawa, S. L. Braunstein, P. van Loock, and A. Furusawa, Nature Physics **5**, 541 (2009).

[2] N. Lee, H. Benichi, Y. Takeno, S. Takeda, J. Webb, E. Huntington, and A. Furusawa, Science **332**, 330 (2011).

[3] H. Yonezawa, D. Nakane, T. A. Wheatley, K. Iwasawa, S. Takeda, H. Arao, K. Ohki, K. Tsumura, D. W. Berry, T. C. Ralph, H. M. Wiseman, E. H. Huntington, and A. Furusawa, Science **337**, 1514 (2012).

[4] S. Takeda, T. Mizuta, M. Fuwa, P. van Loock, and A. Furusawa, Nature **500**, 315 (2013).

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[6] G. Masada, K. Miyata, A. Politi, T. Hashimoto, J. L. O'Brien, and A. Furusawa, Nature Photonics **9**, 316 (2015).

Exploring quantum phases of matter with light

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Photons are highly coherent, long-lived excitations with a diverse set of applications in quantum optics, quantum communication, and quantum computation. However, by nature, photons are fragile — as easy to destroy as to create — and they do not interact. Efforts to work directly with photons for carrying and processing information, classically or quantum mechanically, thus require coupling light to matter. I will examine how exquisite control of light and matter coupling leads to increasingly exotic regimes where photons organize into new phases of matter.

As an example case, we first focus our efforts on the creation of fractional quantum Hall states for light. This example highlights challenges in single-particle physics, such as the creation of synthetic gauge fields for photons; nonlinear optics, including developing strong photon-photon interactions sufficient for fractional quantum Hall regimes; and fundamental questions about stabilizing near equilibrium many-body states of light via artificial chemical potentials.

We then consider exploration of field theoretic phase transitions by use of optomechanical devices. The extended excitations of mechanical resonant structures couple to the radiation pressure of light in an optical cavity, giving rise to novel long-range interactions and different classes of non-local phase transitions. We focus specifically on realization of a Z2 phase transition – buckling of a thin membrane – driven entirely by radiation pressure, and consider extensions of these techniques to continuous groups.

Quantum engineering using hybridization: When 1+1 > 2

W.J. Munro[1], Y. Matsuzaki[1], S. Dooley[2], E. Yukawa[2], K. Kakuyanagi[1], H. Toida[1], K. Semba[3], H. Yamaguchi[1], K. Nemoto[2] and S. Saito[1]

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Quantum information enabled technologies have reached an interesting stage in their development where we can now in principle engineer composite systems to exploit the best properties of these individual systems, or use one system to tailor the properties of the second system. We illustrate this with a hybrid approach (Figure 1) involving a superconducting flux qubit strongly coupled to an electron spin ensemble [1]. We show basic control over this composite system by transferring information from the flux qubit to the ensemble, storing it their, and then subsequently retrieving it [2]. Unfortunately the storage time (coherence time) in the ensemble is severely limited by inhomogeneous broadening. We can however tailor this distribution by either a natural strain field or by an artificial means to create collective long-lived dark states [3]. Our approach opens up the possibility for truly long lived multimode quantum memories, solid-state microwave frequency combs, optical to microwave quantum transducers and the generation of squeezed coherent spin state (one-axis or two-axis twisting) for metrological applications [4]. It may also provide a new route cavity QED experiments with strongly interacting particles.

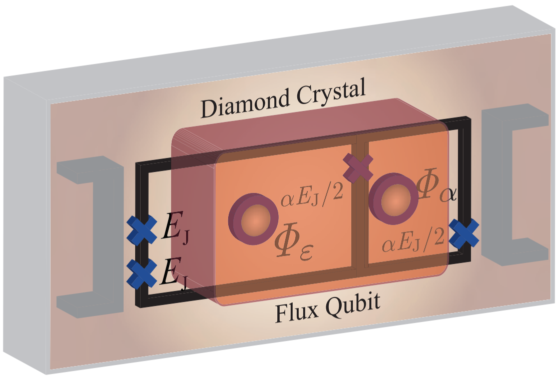

Figure 1: Schematic illustration of a superconducting flux qubit coupled to an NV− center ensemble.

[1] X. Zhu *et al.*, Nature **478**, 221–224 (2011).
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[3] X. Zhu *et al.*, Nature Communications **5,** 3424 (2014).
[4] S. Dooley *et al.*, A hybrid-systems approach to spin squeezing (2015)

Towards quantum frequency conversion between microwaves and light using rare-earth dopants

Xavier Fernandez-Gonzalvo[1] Yu-Hui Chen[1], Chunming Yin[2], Sven Rogge[2] and Jevon J. Longdell[1]

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Superconducting qubits have advanced significantly in recent years, but they have limitations. They can't be coupled directly to optical photons and so lack a mechanism for long distance quantum communication. And while the coherence times have improved greatly recently they are still much shorter than what has been achieved in optically addressed spin systems. Both of these limitations can be overcome with a device that can transfer quantum states encoded in microwave photons into those that are encoded in optical photons.

We have proposed (PRL 113,203601) implementing this quantum transducer using rare earth ion dopants that are simultaneously coupled to microwave and optical resonators, and are currently working towards the implementation. The approach can be considered as a resonator-enhanced version of the Raman-heterodyne spectroscopy, often used for characterising hyperfine structure in rare earth systems

I will present results showing low efficiency frequency conversion with a microwave resonator but single pass optics, as well as more recent results using both a microwave and optical resonator. The microwave splitting in these experiments was achieved by splitting the Kramers degeneracy of the electronic ground state with a magnetic field. This magnetic field makes the use of 3D superconducting resonators problematic. An alternative is to use the hyperfine structure of Er-167 the one isotope of Er with nuclear spin. I will also show results of coupling a broadly tuneable, superconducting, 3D microwave resonator to Er-167 in YSO. The spectra we see at zero magnetic field is not well explained by the spin Hamiltonian parameters derived at higher magnetic fields, and we see a splitting in the peaks which we tentatively ascribe to super-hyperfine coupling. This suggests the possibility of transferring coherence from the erbium electron spin to a neighbouring yttrium nuclear spin.

Fast Qubit Readout from Longitudinal Coupling

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An ubiquitous methods for superconducting qubit readout relies on transversally coupling a qubit to a strongly detuned microwave resonator. In this dispersive regime, the qubit imparts a state-dependent frequency change on the resonator which can be detected. In this talk, we show that it is possible to realize fast and high-fidelity quantum nondemolition qubit readout instead using longitudinal qubit-oscillator interaction. This is accomplished by modulating the longitudinal coupling at the cavity frequency. The qubit-oscillator interaction then acts as a qubit-state dependent drive on the cavity, a situation that is fundamentally different from the standard dispersive case and is advantageous for several reasons that we will be discussed. Furthermore, single-mode squeezing can be exploited to exponentially increase the signal-to-noise ratio of this readout protocol. We present an implementation of this longitudinal parametric readout in circuit quantum electrodynamics and a possible multiqubit architecture.

On-demand creation and detection of single microwave photon

J. S. Tsai

Riken and Tokyo University of Science

Recently, we have achieved on-demand single microwave photon creation [1]. Moreover, we have succeeded in a single-shot detection of single microwave photon with an impedance matched Λ system in a driven circuit QED system that consist of a superconducting flux qubit and a superconducting resonator [1], amplified with a Josephson parametric phase-locked oscillator [2]. Speculations about the impacts of these technologies to quantum information will be discussed.

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Quantum Control & Quantum Error Correction with Superconducting Circuits

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We have developed an efficient quantum control scheme that allows for arbitrary operations on a cavity mode using strongly dispersive qubit-cavity interaction and time-dependent drives [1,2]. Moreover, we have discovered a new class of bosonic quantum error correcting codes, which can correct both cavity loss and dephasing errors. Our control scheme can readily be implemented using circuit QED systems, and extended for quantum error correction to protect information encoded in bosonic codes. In addition, engineered dissipation can also implement holonomic quantum computation using superconducting circuits [4].

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[4] Albert, *et al.*, arXiv: 1503.00194

CMOS platform for silicon spin qubits

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CEA, INAC and Université Grenoble Alpes, 17 Rue des Martyrs, F-38000 Grenoble, France

In the last few years, silicon-based spin qubits have experience a tremendous progress. In particular, very long spin coherent times have been obtained following the introduction of isotopically purified ^{28}Si epilayers, where hyperfine coupling is largely suppressed. This has enabled the realization of one- and two-qubit gates with very high fidelities. In the prospect of large-scale qubit integration, the implementation of silicon spin qubits onto an industrial CMOS platform would be highly beneficial. With this in mind, we have been investigating the possibility to realize spin qubit devices using an industry-standard CMOS platform. In this talk, I will present an up-to-date overview of our progress.

We have shown that both few-electron and few-hole quantum dots can be formed in silicon nanowire transistors based on 300-mm silicon-on-insulator technology. I will present the first realizations of double quantum dots in dual-gate nanowire transistors. We have observed the spin-blockade effect (useful for spin readout) and obtained the first experimental signatures of hole-spin resonance. In the case of holes, g-factors are found to be anisotropic and gate dependent providing a pathway to electrically driven spin manipulation via the g-tensor modulation resonance mechanism with Rabi frequencies as large as ~100 MHz.

Cavity quantum electrodynamics using semiconductor quantum dots embedded in photonic crystal nanocavities

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Semiconductor quantum dots (QDs) coupled with photonic crystal (PhC) nanocavities form a robust platform for studying cavity quantum electrodynamics (QED). The large oscillator strengths of QDs and near-diffraction-limited optical confinement of PhC nanocavities facilitate strong light matter interaction with a high Rabi frequency in the tens of GHz range, suitable for developing ultrafast photonic quantum information devices. QD-based systems also offer unique opportunities for cavity QED study, such as bright luminescence which enables the quick determination of the emission spectrum, complex-enough excitonic states with spin degrees of freedom, and easy optical access with sophisticated free-space and/or fiber optics. However, some drawbacks are found in such QD-based systems, including unpredictable light-matter coupling strength due to unknown QD position in the nanocavity, and relatively-low cavity *Q*-factors that hinder deeper investigation of the strong coupling regime.

In this presentation, we will discuss (1) atomic channel spectroscopy of a single-emitter cavity QED system in the strong coupling regime[1] (Fig. 1.(a)), taking advantage of the flexible optical access. We will also discuss our efforts to overcome the above drawbacks, such as (2) a nm-precision technique for detecting QD locations in nanocavities[2] (Fig. 1(b)), and (3) the fabrication of high *Q*-factor nanocavities with very small mode volumes. These novel technologies will help deepen our understanding of solid state cavity QED physics and facilitate the implementation of ultrafast on-chip photonic quantum information devices.

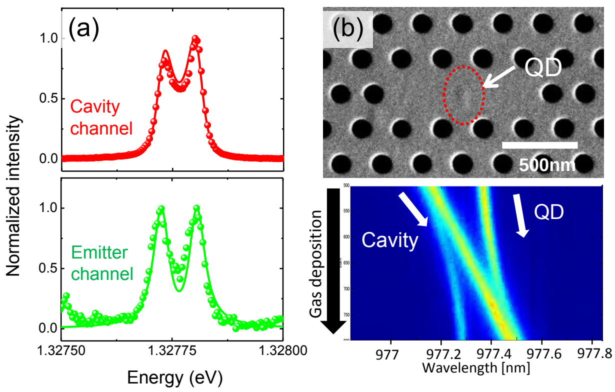

Fig. 1. (a) Detection channel dependent vacuum Rabi spectra. (b) Detecting the QD location in a cavity and measuring its corresponding spectra.

Reference: [1]Y. Ota, *et al*., Phys. Rev. Lett. **114**, 143603 (2015). [2]K. Kuruma, Y. Ota, *et al*., in preparation.

Manipulation of Single Flying Electrons for Quantum Electron Optics

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Quantum electron optics is a field in which one manipulates quantum states of propagating electrons. Combined with technologies for confining and manipulating single electrons, it allows us to investigate the scattering and interference of electrons in a unit of a single electron. The necessary elements of quantum electron optics experiments include single electron beam splitter, phase shifter, Coulomb coupler, single electron source and detector, spin-orbit path and electron-pair splitter.

In this talk, we present development of some of these elements. The beam splitter and phase shifter are implemented in our original two-path interferometer [1-3]. This interferometer has been shown to be the only reliable system for the measurement of the transmission phase shift of electrons [4,5]. To suppress decoherence induced by the electron-electron interaction and enhance the interference visibility, we recently developed a two-path interferometer of depleted channels, where single electrons are injected by means of surface acoustic waves (SAWs). We also confirmed that a single electron in a static quantum dot (single electron source) can be adiabatically transferred into a SAW-driven moving quantum dot, a necessary ingredient for achieving the high interference visibility of a single flying electron.

Quantum electron optics also targets the manipulation of spins of flying single electrons. We found that the spin information of one or two electrons can be transferred between distant quantum dots, which work as the single electron source and detector, with the fidelity limited only by the spin flips prior to the spin transfer [6,7]. We also realized an electron-pair splitter that can be used to split spin-entangled electrons in a moving dot into different moving dots. Combined with single spin manipulation using the spin-orbit interaction (spin-orbit path) [8], this splitter should allow for Bell measurement of electron spins.

This work is in collaboration with S. Takada (now at Institut Neel), R. Ito and K. Watanabe at the University of Tokyo, B. Bertrand, S. Hermelin, T. Meunier, and C. Bäuerle at Institut Neel, and A. Ludwig and A. D. Wieck at Ruhr-Universität Bochum.

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Spontaneous current oscillation in 2D electrons on liquid helium caused by a strong intersubband excitation

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Spontaneous spatiotemporal ordering often occurs in systems driven away from equilibrium [1]. Recently, strong nonequilibrium phenomena are observed in surface state electrons (SSE) formed on liquid helium surface [2]. In particular, under a quantizing magnetic field applied perpendicular to the surface, when the frequency of microwave which excites SSE from the ground subband to first excited subband becomes commensurate with the cyclotron frequency, the effect is extremely anomalous, that is, the diagonal conductivity, σ_{xx}, vanishes, implying dissipationless electron transport [3]. When microwave excitation is applied, SSE are pulled toward the peripheral edge, overcoming the confining electrostatic potential and producing a strong depletion (up to 50%) of charge distribution at the center resulting in a radial electric field. This pattern remains until microwave is turned off, when the system returns to the equilibrium distribution [4]. Moreover, it is found that the charge redistribution is not only static but also dynamic, namely, the charge oscillations are spontaneously generated in the audio-frequency range [5].

In this talk I will describe our recent observations of these anomalous phenomena in strongly nonequilibrium SSE on liquid He.

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Exciton-polariton dynamics in structured complex potentials

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Exciton-polaritons, hybrid bosonic particles composed of a cavity photon and semiconductor exciton may achieve a form a Bose-Einstein condensation despite the initial lack of confining potentials, due to the open-dissipative nature of this system. To properly control condensate dynamics and to create new phases however, techniques for flexibly and strongly confining the polaritons to an arbitrary geometry are essential [1]. The use of newly developed combinations of semiconductor fabrication techniques [1,2] and optically defined potentials [3,4], has led to recent observations of distinct topological dynamics and non-equilibrium states in the non-equilibrium exciton-polariton condensate.

Notably, it has recently been recognized that, as a result of this open-dissipative nature, the exciton-polariton condensate is strongly non-Hermitian, and is an ideal platform to study the large scale dynamics uniquely characteristic of such systems. I will present the results of experiments using two distinct methods of spatially structuring the gain and loss (imaginary potential) of a trapped polariton condensate so as to engineer *complex* potentials and drive such non-Hermitian dynamics. The first uses an optically defined soft-walled chaotic billiard potential which exhibits exceptional points [4], and the second uses second uses precise semiconductor fabrication techniques to create arbitrarily structured complex 2D lattices [1]. Opportunities for exploitation of such non-Hermitian dynamics towards novel coherent polariton devices will be discussed.

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Disturbance-free, electron holographic observation of electrons' motion by electric field variations

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Electron holography is a disturbance-free observation technology [1], which utilizes the interference effect of the electron wave, and it has been applied to the electromagnetic field visualization. In this study, we extend this technology to visualization of electrons' motion by detecting the electric field variations (Fig. 1). By changing geometrical configurations of insulating specimens charged positively due to the electron irradiation, secondary electrons emitted from the specimens are accumulated around the surface of the insulating specimens and the collective motion of electrons is dynamically observed through amplitude reconstructing process [2].

Figure 2(a) shows one of our experimental results of visualizing orbits of secondary electrons around charged microfibrils of a sciatic nerve tissue with a W probe inserted. Red regions correspond to areas where the electric field varies due to the motion of electrons. When the bias voltage of 5V between the microfibrils and the W probe is applied, the size of the orbit becomes smaller as shown Fig. 2(b). Finally the present result of visualizing collective motion of electrons at the nanometer scale through electron holographic interferometry at the micrometer scale is briefly discussed in terms of the field equations, i.e., Maxwell's equations and Einstein's field equations.

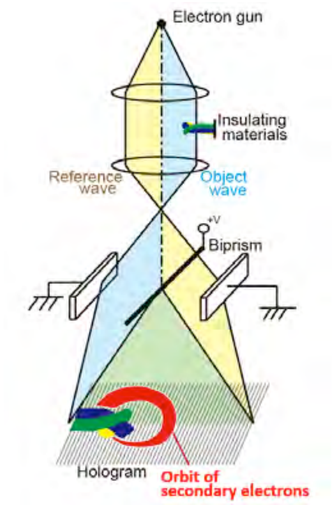

Fig. 1 Schematic illustration showing the imaging process of a hologram. Blue and yellow regions correspond to the object and reference waves, respectively.

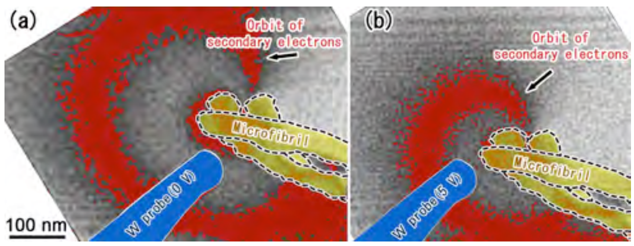

Fig. 2 Reconstructed amplitude images showing the orbits of secondary electrons around positively charged microfibrils. Voltages of an inserted W probe are (a) zero and (b) 5 V.

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Quantum optimal control and its applications

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Quantum computation provides great speedup over classical counterpart for certain problems, such as quantum simulations, prime factoring and database searching. One of the challenges for realizing quantum computation is to execute precise control of the quantum system in the presence of noise.

Herein, we present methods to quantitatively characterize the noises during the gate operations and demonstrate the strategies to fight against these noises. Optimal quantum control has been applied to realize high fidelity quantum gates. We demonstrate a universal set of logic gates in nitrogen-vacancy centers with an average single-qubit gate fidelity of 0.99995 and two-qubit gate fidelity of 0.992. These high control fidelities have been achieved in the ^{13}C naturally abundant diamonds at room temperature.

Entanglement Prethermalization in a Bose Gas

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Thermalization in an isolated quantum system is a long-standing subject since von Neumann. Recent experimental advances in ultracold atoms have enabled one to experimentally explore when and how (pre)thermalization occurs. In this talk, we propose a new type of prethermalization in a coherent split experiment of a quasi one-dimensional Bose gas. Remarkably, entanglement persists even under the situation of interacting many particles and significantly affects prethermalized states [1].

[1] E. Kaminishi, T. Mori, T. N. Ikeda, and M. Ueda, Nat. Physics DOI:10.1038/MPHY3478

Squeezed and displaced Fock bases and Schrödinger's Cat

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I will describe a series of experiments in which we have engineered spin-oscillator couplings to realize state-engineering, control and diagnostics for the quantum harmonic oscillator. Initial work generated and analyzed squeezed states by reservoir engineering [1], providing a resource for generating squeezed wavepacket analogues to the well known Schrodinger's cat states, observing re-coherence after separating the entangled wavepackets by up 20 times the ground state r.m.s. extent, which corresponds to more than 60 times the width of the squeezed wavepacket [2]. Using a non-squeezed cat, we have demonstrated a measurement-based post-selection scheme to dis-entangle the spin and motion, and reveal the quantum interference between the two separated wavepackets. Wigner function tomography of the resulting state was performed by driving Jaynes-Cummings physics in a displaced-Fock basis for a range of displacements. For larger states, projection onto the energy eigenbasis fails due to the increase in the energy uncertainty. To overcome this problem, we have used a squeezed Fock basis for the reconstruction with up to 8 dB of squeezing. This allowed us to directly observe the quantum interference between two states with a phase space separation of 15.6, corresponding to separations in real space of 240 nm for a wavepacket r.m.s. size of 8 nm. In separate work in a cryogenic apparatus, we have demonstrated the ability to control the trapping potentials on nano-second timescales, providing access to the sudden approximation in quantum mechanics, and allowing the demonstration of control of quantum states with up to 10 kilo-quanta [3].

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Quantum spin dynamics with ultracold atoms

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As controlled solid-state systems realize an artificial atom of a two-level system, well-arranged atoms can mimic solid-state materials. Ultracold atomic gases in optical lattices realize strongly-correlated quantum systems described by the Hubbard model or the Heisenberg spin model. Recently, for such systems, powerful tools of single-atom-resolved detection and manipulation have been developed. These new techniques enable us to access non-equilibrium quantum dynamics of such systems, beyond the conventional pump-probe experiments of materials with ultrafast laser spectroscopy. In this talk I will present experimental results on the quantum dynamics of a mobile spin impurity, or magnon, in a one-dimensional Heisenberg spin chain created by ultracold bosonic atoms in optical lattices. After preparing a spin-polarized chain, we deterministically introduced a single magnon by selectively flipping a spin at the center of the chain, and observed its coherent dynamics with high resolution in space and time [1]. Furthermore, transverse spin correlations were measured by applying a global $\pi/2$ rotation before imaging. Combining longitudinal and transverse correlation measurements, we detected spin entanglement, which is generated and transferred through the single-magnon dynamics [2].

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Chiral Nanophotonics and Quantum Optics

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When light is strongly transversally confined, significant local polarization components that point in the direction of propagation arise. In contrast to paraxial light fields, the corresponding intrinsic angular momentum of the light field is position-dependent - an effect referred to as spin-orbit interaction of light. Remarkably, the light's spin can even be perpendicular to the propagation direction. The interaction of emitters with such light fields leads to new and surprising effects. For example, when coupling gold nanoparticles or atoms to the evanescent field surrounding a silica nanophotonic waveguide, the intrinsic mirror symmetry of the particles' emission is broken. This allowed us to realize chiral nanophotonic interfaces in which the emission direction of light into the waveguide is controlled by the polarization of the excitation light [1] or by the internal state of the atoms [2], respectively. Moreover, we employed this chiral interaction to demonstrate nonreciprocal transmission of light at the single-photon level through a silica nanofiber [3]. The resulting optical diode is the first example of a new class of nonreciprocal nanophotonic devices which exploit the chiral interaction between quantum emitters and transversally confined photons.

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An all-fiber cavity QED system with a nanofiber and a trapped atom

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A cavity quantum electrodynamics (QED) system, where an atom is coupled to electromagnetic field confined in a microcavity, is suitable for studying dynamics of interaction between an atom and light. In the strong coupling regime of cavity QED, where the rate of the coherent exchange of energy between the atom and the cavity exceeds the rate of the dissipation of the system (the spontaneous emission of the atom and the leakage of light from the cavity), the coherent nature of the system can be preserved in its dynamics. Furthermore, because of this strong coupling between the atom and light, a cavity QED system can be utilized as a quantum interface between a stationary qubit (atom) and a flying qubit (photon). In this context, an all-fiber cavity QED system is desirable for realization of a fiber-based quantum network. In this talk, I will present our recent experiments on the realization of an all-fiber cavity QED system with a nanofiber and an optically trapped single cesium atom in the strong coupling regime [S. Kato and T. Aoki, Phys. Rev. Lett. 115, 093603 (2015)].

Th08

Quantum spin Hall effect of light

K.Y. Bliokh[1] and Franco Nori[1,2]

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Maxwell's equations, formulated 150 years ago, ultimately describe properties of light, from classical electromagnetism to quantum and relativistic aspects. The latter ones result in remarkable geometric and topological phenomena related to the spin-1 massless nature of photons. By analyzing fundamental spin properties of Maxwell waves, we show that free-space light exhibits an intrinsic quantum spin Hall effect—surface modes with strong spin-momentum locking. These modes are evanescent waves that form, for example, surface plasmon-polaritons at vacuum-metal interfaces. Our findings illuminate the unusual transverse spin in evanescent waves and explain recent experiments that have demonstrated the transverse spin-direction locking in the excitation of surface optical modes. This deepens our understanding of Maxwell's theory, reveals analogies with topological insulators for electrons, and offers applications for robust spin-directional optical interfaces.

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K.Y. Bliokh, F.J. Rodriguez-Fortuno, F. Nori, A.V. Zayats, *Spin-orbit interactions of light*. Nature Photonics 9, p. 796–808. 13-pages review, including some of our results. URL: http://www.nature.com/nphoton/journal/v9/n12/full/nphoton.2015.201.html

Quantum Random Access Memories with Multimode Circuits

David Schuster

University of Chicago

Quantum computing has made tremendous progress in recent years. Coherence times have increased by over a 10000x in the past decade, and the fidelity of gates is approaching the threshold for fault tolerant error correction. Circuits are also growing in size with several bit circuits having been demonstrated. Growing circuit complexity brings with it challenges about how to control large numbers of bits. I will describe experiments in which we realize a quantum random access memory that allows the control of many (10-20) memory bits (resonators) with a single Josephson junction qubit.

Simulating Topological Band Structure Using Quantum Walks

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Classical random walks characterize a variety of stochastic phenomena ranging from physics to finance and form the basis of computational tools spanning fields from medical imaging to social networking. More than 20 years ago, Aharonov et. al. introduced the notion of a quantum random walk, where the walker possesses an additional spin degree of freedom and can exist in a coherent superposition of lattice sites. Interference between different scattering paths on the lattice determines the resulting dynamics, which mirror those arising in certain spin-orbit coupled Hamiltonians. Depending on symmetry, such Hamiltonians can feature topological invariants with quantized values robust to local perturbations—the hallmark of exotic phenomena such as unconventional edge states in topological insulators and quantized charge transport in the Thouless pump. Direct measurement of topological invariants remains a major experimental challenge on account of their non-local character. Here, we present the first measurement of a topological invariant in a quantum random walk, thereby directly delineating between two distinct classes of walks: topologically trivial and non-trivial. Our walk is realized in a cavity quantum electrodynamics (cQED) architecture consisting of a superconducting transmon qubit dispersively coupled to a microwave cavity mode. By adiabatically deforming the Hamiltonian during the quantum walk, we imprint the topology of the effective band-structure onto the relative phase of a cavity Schrödinger cat state; one component of the cat lies dormant while the other undergoes the walk. Using Wigner tomography, we directly observe the expected values of the invariant 0 (trivial) and π (topological) in the two phases associated with the canonical Su-Schrieffer-Heeger model of polyacetylene. Our protocol can be readily extended to a larger Hilbert space, where quantum walks can realize a digital quantum simulation of all non-interacting topological phases known in one and two dimensions as well as potentially unexplored landscapes in three dimensions.

Hybrid cQED architecture as a model system for non-equilibrium physics in condensed matter

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The interaction between light and matter at its most elementary level, i.e. between single quanta of photons and atoms, has for many years been probed using quantum electrodynamics. The field was first developed by enclosing atoms and photons within an optical cavity, cavity quantum electrodynamics (CQED) [1], and then further by implementing the architecture on chip, so-called circuit electrodynamics (cQED) [2]. Here we show how a hybrid cQED architecture may act as a model system for investigating non-equilibrium physics in condensed matter and as a method to distantly couple artificially engineered quantum dots (QDs).
Our hybrid architecture scheme consists of a microwave cavity (~6 GHz) coupled to a pair of spatially separated SiGe double quantum dots that may be driven in and out of equilibrium. The electron-photon coupling scheme is analogous to the electron-phonon coupling prevalent in other condensed matter problems. First we show the scheme for distantly coupling QDs. Then we describe our experimental efforts to incorporate QDs into the cQED architecture. Finally, we conclude with prospects for coupling the electron spin within the quantum dots to the cavity photon mode. We look at the feasibility of modulating the coupling between spins and cavity to realize both resonant spin-photon interactions and fast non-demolition readout of the spin state.

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Multi-Particle Quantum Dynamics under Continuous Observation

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Recent experimental developments [1,2] in ultracold atoms are now approaching the level at which a real-time observation of quantum many-body dynamics can be performed [3]. Against such a backdrop, we formulate and discuss the dynamics of quantum many-body systems under real-time spatially resolved measurement [4]. We show that, in the continuous measurement limit, the indistinguishability of identical particles results in the complete suppression of relative positional decoherence. Consequently, the indistinguishability persists in the course of quantum dynamics under weak continuous observation. We perform numerical simulations for the system of atoms trapped in an optical lattice, and demonstrate such robustness of the dynamics of indistinguishable particles against continuous observation. Our results can be applied for the purpose of feedback control of quantum many-body systems, which may be realized in future subwavelength spacing lattice systems.

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Circuit-QED-based quantum architectures relying on longitudinal interactions

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Cavity QED addresses several aspects of the interaction between a real atom via its electric dipole moment to the quantized radiation field of a three-dimensional cavity. Such a system can be described by the coupling of a coherent two-level system via its transverse degree of freedom to a quantum harmonic oscillator. Circuit QED is the exact analog of cavity QED experiments with artificial atoms made from superconducting nanostructures. This field of research is a promising route toward the realization of scalable architectures for quantum information processing. The possibility to integrate these circuits at large scale is a rather appealing aspect of this scheme.

Among systems encountered in atomic physics, trapped ions offer several advantages such as long coherence times, flexible approaches for entanglement generation, and high-fidelity readout based on the electron shelving technique. Cirac and Zoller first proposed a scalable approach where entanglement generation is provided by a mechanism of conditional phase accumulation based on sideband transitions. We discuss another analogy between the physics of trapped ions and a different configuration of circuit QED wherein artificial atoms are coupled to bosonic modes via their longitudinal degree of freedom. On the basis of this observation, we describe a scalable architecture to process quantum information with superconducting qubits relying on sideband transitions in the spirit of the Cirac-Zoller scheme.

In order to tailor tunable interactions, ion traps offer several alternatives to sideband transitions. Sørensen and Mølmer proposed a way of generating entanglement via spin-dependent forces whose main asset is that it does not require to initialize the state of the trap via sideband cooling. We consider several ways to implement two-qubit gates in this configuration, and we quantify their corresponding fidelity. This analysis provides the basis for a discussion on the relevance of entanglement generation and readout based on either sideband transitions or spin-dependent forces for the development of a large-scale quantum architecture with Josephson-junction-based artificial atoms.

Measurement of gate fidelity in a superconducting 3D transmon qubit

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Estimating and improving the error rate of a quantum gate is the key to implement practical quantum computation. We present our measurement of the fidelity of single-qubit gates acting on a superconducting transmon qubit strongly coupled to a 3D aluminum cavity. Two methods, randomized benchmarking (RB) [1,2] and quantum process tomography (QPT) [3], are employed to measure the fidelity of the quantum gates. Using optimized Gaussian pulse shaping, interleaved RB [2] showed high fidelity near 99.5% for four π pulses, and the QPT revealed near 96% fidelity for two π/2 pulses. Apparently higher error rate in tomography was expected due to the presence of SPAM(state preparation and measurement) errors. Extension of these fidelity measurement methods to two-qubit gates for entanglement operations, and precise estimation of the improvement by DRAG (derivative removal via adiabatic gate) pulse shaping are under way.

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Ground State Electroluminescence

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Electroluminescence, the emission of light in the presence of an electric current, provides information on the allowed electronic transitions of a given system. Our work shows that, together with usual electroluminescence, systems in the ultrastrong light-matter coupling regime emit a uniquely quantum radiation when a flow of current is driven through them. While standard electroluminescence relies on spontaneous emission from excited states of the system, the process we describe extracts bound photons from the dressed ground state and it has peculiar features that unequivocally distinguish it from usual electroluminescence.

P06

Mobile quantum cryptography with a quantum sneakernet.

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A quantum sneakernet is a recent proposal where active, error corrected quantum memories are locally entangled and then physically transported from source to destination to provide a intercontinental Bell link at ultra high fidelity. These error corrected memories consist of O(1000) physical qubits protected by the topological planar code, and dependant on the physical parameters of the candidate system can result in effective coherence times of weeks and/or months at an infidelity of 10^(-10) and at high enough qubit densities can result in transpacific quantum networks at rates above Terahertz. One of the interesting applications of such a system is the ability to allow Bell pairs to be distributed between land and mobile platforms. This would allow for E91 QKD protocols to be implemented on platforms such as aircraft, naval ships and even perhaps space based platforms, something difficult for a traditional quantum repeater system designed to distribute end-to-end entanglement.

The memory stick itself contains some finite number of memory units, each containing sufficient numbers of physical qubits to perform continuous error correction for a single encoded piece of quantum information. The physical qubits in the memory stick are encoded using the Planar code allowing for a single qubit of information to be encoded with the strength of error correction scaling with the total size of the lattice.

Once quantum memories of long effective coherence times are available, distributing entanglement can be relegated to physically transporting these active quantum memories. This allowed us to present a network with > THz speeds with high density technologies such as silicon and diamond. Distributing a single memory unit from source to destination using physical transport allows for us to implement QKD protocols such as E91 in an identical way to a Bell state prepared using a traditional repeater network. The great benefit of this physical distribution is that there is no quantum architecture necessary along the communications route. This allows for us to distribute Bell states to any location where a classical transport route is available.

This has clear applications for QKD that is difficult (or if not impossible) for traditional repeater systems, namely the distribution of high fidelity Bell states between ships, aircraft, submarines, personal devices and even space based platforms. A sneaker net design may be the best hope for achieving mobile QKD nodes based on entanglement.
Entanglement distribution on mobile platforms have clear applications for the military. Aircraft deployment, naval ship deployment and importantly submarine deployment of QKD nodes would arguably be impossible with any traditional technology. In contrast, a sneakernet approach only requires the loading of enough memory units while at port to cater for any sensitive communications necessary during deployment.

Spin squeezing via interaction with a dissipative qubit

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The generation of non-classical states of large quantum systems has attracted significant attention due to the potential of such states in emerging quantum technologies, such as quantum metrology and sensing. For instance, it is well known that highly entangled states of N spin-1/2 particles, such as spin squeezed states, can -- in principle -- be exploited to increase the precision of some measurements by a factor that scales with N^{1/2} compared to the best precision that is achievable with a separable state. Interestingly, an improvement in the precision is even possible in the presence of certain types of realistic decoherence, although the scaling of the improvement is reduced to N^{1/4}. The motivation of the work described here is the generation of such spin squeezed states, starting from an easily prepared separable state of the spin system.

Solid state spin defects, such as nitrogen vacancy centres or electron donor spins in silicon, are particularly promising candidate spin systems due to their long coherence times. However, to generate entanglement it is clear that we require some sort of interaction between the spins. Although it has been proposed that this can be achieved using the natural magnetic dipole-dipole interaction between the spins, in practice this is difficult because any spin will interact very weakly with a distant spin (the strength of the dipole-dipole coupling between two spins scales as r^{-3} where r is the distance between the two spins). Since this interaction is weak it will be challenging to generate highly entangled states within the spin coherence time. Instead, we adopt a hybrid-systems approach where the spins are allowed to interact with an auxilliary system. This interaction with the auxilliary system can induce coupling between the spins (including long range interactions between distant spins) which can then be exploited to generate the necessary entanglement. In this work we consider the interaction of a short-lived, dissipative ancillary qubit with a long-lived spin system, and we show that this hybrid-systems approach can be used to generate relatively large spin squeezed states. This is a typical feature of the hybrid-systems approach: the strengths of both the auxilliary system and the system of interest are exploited to generate dynamics that would be difficult to generate with either system individially.

Quantum optics with giant artificial atoms

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In quantum optics experiments with both natural and artificial atoms, the atoms are usually small enough that they can be approximated as point-like compared to the wavelength of the electromagnetic radiation they interact with. However, a recent experiment coupling a superconducting qubit to surface acoustic waves shows that a single artificial atom can be coupled to a bosonic field at several points which are wavelengths apart [1]. This situation could also be engineered with an xmon qubit coupled to a microwave transmission line [2].

Here, we present results of theoretical studies of such "giant artificial atoms" [2, 3, 4]. In the Markovian regime, where the travel time between coupling points is negligible, we find that interference effects due to the positions of the coupling points give rise to a frequency dependence for the strength of the coupling between the giant artificial atom and its surroundings [2]. The Lamb shift of the atom is also affected by the positions of the coupling points. We discuss possible applications for these frequency dependencies (which can be designed). In the non-Markovian regime, where the distance between coupling points is large, an excited giant atom exhibits revivals and non-exponential decay [3]. In this regime, we have also studied novel features that occur in the correlation function $g^2(t)$. Finally, we also explore setups with several giant atoms coupled to a transmission line in various configurations [4].

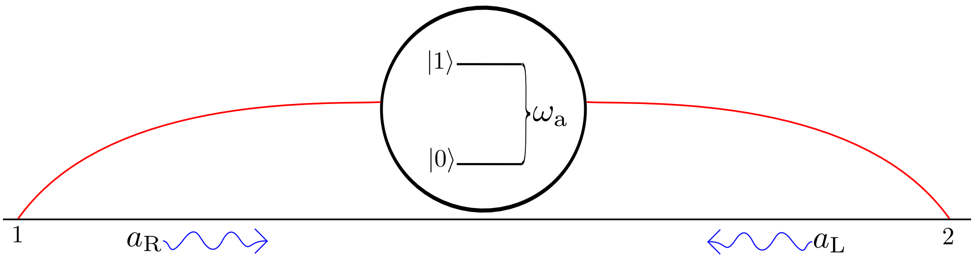

Figure 1: A sketch of a giant artificial atom, coupled to right- and left-moving modes in a one-dimensional transmission line at two points which are wavelengths apart.

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Experimental fault-tolerant universal quantum gates with solid-state spins under ambient conditions

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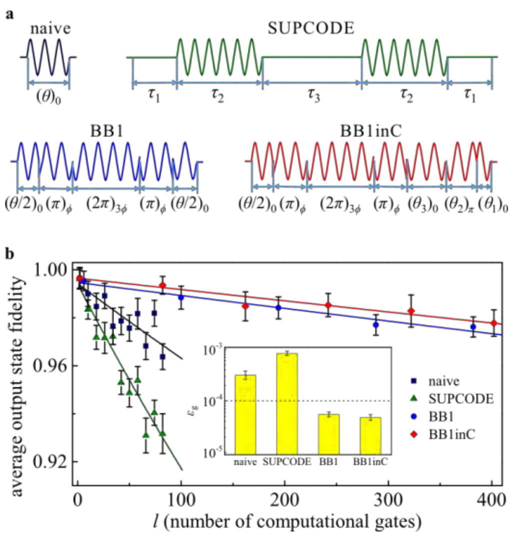
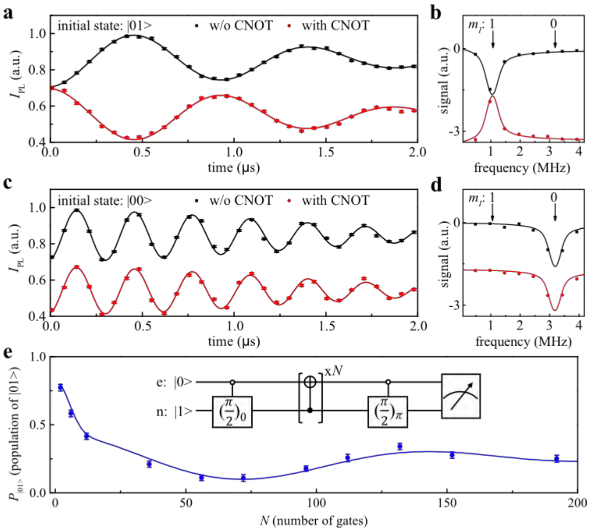
Quantum computation provides great speedup over its classical counterpart for certain problems. One of the key challenges for quantum computation is to realize precise control of the quantum system in the presence of noise. Control of the spin-qubits in solids with the accuracy required by fault tolerant quantum computation under ambient conditions remains elusive. Here, we quantitatively characterize the source of noise during quantum gate operation and demonstrate strategies to suppress the effect of these. A universal set of logic gates in a nitrogen-vacancy center in diamond are reported with an average single-qubit gate fidelity of 0.999952 and two-qubit gate fidelity of 0.992. These high control fidelities have been achieved at room temperature in naturally abundant ^{13}C diamond via composite pulses and an optimised control method. To the best of our knowledge, the results stand for the state of art in high-fidelity control of solid-state spins under ambient conditions





ac-spectroscopy of spin-orbit coupled spins in double quantum dots

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Controlling the dynamics of a few electrons in quantum dot systems is fundamental for various spin and charge based semiconductor devices. The application of time periodic fields can induce transitions between quantum states due to spin rotations. These can be detected electrically, namely, by measuring the current flowing through the device.

In this work we study theoretically electron-spin-resonance effects in a double quantum dot tuned in the spin blockade regime. The spins are coupled via interdot hopping as well as spin orbit interaction and are driven by an ac-electric field. The model is based on a master equation approach that takes into account the periodic driving field within the Floquet approach.

We find that the electrical current through the double dot displays a broad peak due to the spin-orbit interaction. The application of the driving field induces n-photon resonances allowing the singlet-triplet anticrossing point to be probed. We quantify these resonances and find their dependence on applied power and magnetic field. Around the anticrossing point we predict a big difference in the visibility of the resonances that correspond to the same applied frequency but different magnetic field. The theoretical findings are in very good agreement with experiments in double quantum dots formed in Si MOSFET channels [1].

[1] K. Ono et al.

Adiabatic quantum computation using a quantum-mechanical bifurcation of a nonlinear oscillator network

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Recently, artificial nonlinear oscillators have been developed and have achieved both large nonlinearity and low loss simultaneously. As a result, their applications to quantum information science are naturally expected. Although the use of nonlinear oscillators for quantum bits (qubits) has been proposed, their continuous degrees of freedom have not been fully harnessed for quantum computation.

Here we propose a novel quantum computer composed of quantum-mechanical nonlinear oscillators. The oscillator assumed here is a parametrically driven Kerr nonlinear oscillator (Kerr parametric oscillator or KPO for short). As we show, this oscillator can yield a Schrödinger cat state deterministically via its bifurcation with a slowly increasing parametric pump rate. This process is based on quantum adiabatic evolution. Our quantum computer is a network of the KPOs coupled to one another appropriately depending on given problems. We show that the network can find optimal solutions for hard combinatorial optimization problems via its bifurcation process based on quantum adiabatic evolution. In contrast to conventional adiabatic quantum computation or quantum annealing, where quantum fluctuation terms are decreased slowly, nonlinear terms are increased slowly in the present computation. To distinguish them, we refer to the present approach as bifurcation-based adiabatic quantum computation. We present numerical simulation results indicating that quantum superposition and quantum fluctuation work effectively to find optimal solutions.

While most previous computational models for quantum computation use qubits as fundamental components, the present model uses quantum nonlinear oscillators. Moreover, to the best of our knowledge, this harnesses a bifurcation process of a nonlinear oscillator network for quantum computation for the first time. It is also notable that the present model is analogous to a neural network, which is also a network of nonlinear components. Thus, the present scheme will open a new paradigm for quantum computation, nonlinear science, and artificial intelligence.

Generalized Gibbs Ensemble in Nonintegrable Systems with an Extensive Number of Local Symmetries

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Recent experimental progresses using ultracold atomic gases have enabled us to study the dynamics of almost isolated quantum systems. One of the important topics of the relaxation in these systems is whether the conventional (micro-)canonical ensemble can describe the stationary state. Nonintegrable systems that conserve only energy are expected to relax to the canonical ensemble, via the so-called eigenstate thermalization hypothesis (ETH). In contrast, integrable systems do not relax to the canonical ensemble, since they have many conserved quantities. The stationary state in these systems is expected to be described by the generalized Gibbs ensemble (GGE), which takes the conserved quantities into account. Then, the natural question is how many conserved quantities are required for the GGE to describe the stationary state.

In this poster, we show that the GGE is necessary to describe stationary states even in a nonintegrable system if it has an extensive number of local symmetries. We numerically study a nonintegrable model of hard-core bosons with an extensive number of local $\mathbb{Z}_2$ symmetries that lead to many conservation laws. We show that the expectation values of local observables in the stationary states are described by the GGE instead of the canonical ensemble. We argue that this is because the ETH holds true for each symmetry sector, not for the entire spectrum. Next, we modify the model so that it involves only one global $\mathbb{Z}_2$ symmetry or an L-independent number of local $\mathbb{Z}_2$ symmetries. We show that the canonical ensemble works and that the GGE is not necessary in these models.

Analysis of motion of minute quantum machines

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The purpose of this study is to design minute systems with tens degrees of freedom which have certain functions. They are so small that quantum effects are non-negligible. Furthermore effects of entropy arise since the number of quantum states is large, which is an exponential function of the degrees of freedom. We expect that such minute systems can exhibit complex behaviors by fully utilizing the quantum and entropy effects. Furthermore, systems with lower symmetries will have more complex functions than symmetric systems. From these observations, we study fermion systems and frustrated systems, in which quantum and entropy effects are significant, on various lattices which do not have translational symmetry. Although it is difficult to analyze such systems by conventional methods, the thermal pure quantum (TPQ) formulation [1], which is one of the formulation of quantum statistical mechanics, enables us to analyze them. The numerical method based on this formulation allows us to calculate all thermodynamic quantities.

There are varieties of functions, such as calculator and actuator. Among them, we focus on a display. If it is possible to design a system which changes its particle-density distribution depending on temperature, we can regard such a system as a display whose image changes with changing temperature. As an example of such a display we consider a spinless fermion system on a lattice, as shown in Fig.1, with nearest-neighbor interaction and hopping. The system shows four phases, and two of them (II and III of Fig.2) have characteristic distributions of particles, as shown in Fig.2. Our analysis shows that similar four-phase systems can be constructed with a smaller number of lattice sites. We expect it possible to design systems that display more complicated symbols by combining these small systems.

On the poster, we will also present other minute quantum machines, such as a detector of the particle numbers injected into two ports.

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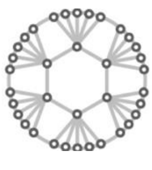

Fig.1 Lattice of display

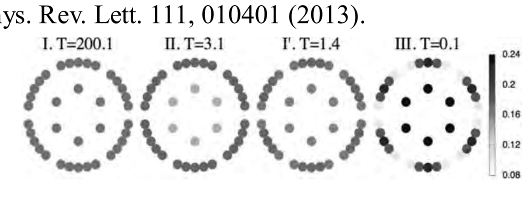

Fig.2 particle-density distribution of display

Bidirectional conversion between microwave and light via ferromagnetic magnons

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Optical and microwave photons are the vital elements in many technologies for quantum information processing. Development of quantum interfaces between optical and microwave photons leads to yet-to-be-realized quantum communication and quantum repeater technologies. While nanomechanical devices and paramagnetic spin ensembles are widely studied for quantum interfaces, we investigate spins in ferromagnets as an alternative candidate [1,2].

Spins in ferromagnets are ordered by the exchange interaction between adjacent spins leading to macroscopic magnetization. Collective excitations in the ferromagnetic spin ensemble, such as in an yttrium-iron-garnet (YIG) sphere, can be described by harmonic oscillator modes and their quanta, magnons.

Here we demonstrate that the bidirectional coherent conversion between optical and microwave photons are possible via magnons in the uniformly precessing magnetostatic mode, called the Kittel mode. The converter consists of two harmonic oscillator modes, a microwave cavity mode and the Kittel mode, where photons in the cavity mode and magnons in the Kittel mode are strongly coupled and hybridized. The conversion efficiency is theoretically analyzed and experimentally evaluated. Improving the coupling strength between the magnons and photons is found to be a critical as well as challenging task for realizing quantum interface. The possible schemes for improving the efficiency are also discussed.

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Anti-ferromagnetic nuclear spin helix and topological superconductivity in ^{13}C nanotubes

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We investigate the RKKY interaction arising from the hyperfine coupling between localized nuclear spins and conduction electrons in interacting carbon nanotubes made of ^{13}C [1]. Using the Luttinger liquid formalism, we show that the RKKY interaction is sublattice dependent, resolving the inconsistency between the earlier work [2,3] and the spin susceptibility calculation in non-interacting nanotubes [4]. The sublattice-dependent RKKY interaction forms $q=\pm 2k_F$ peaks with the Fermi wave number, k_F, and induces a novel *anti-ferromagnetic* nuclear spin helix with a spatial period π/k_F (Figure). The transition temperature reaches up to several tens of millikelvins, due to the feedback effect through the Overhauser field from the ordered nuclear spins. The nuclear spin helix, combining spin and charge degrees of freedom, results in synthetic spin-orbit interaction, which is crucial for non-trivial topology [5]. In the presence of proximity-induced superconductivity, this system has a potential to realize Majorana fermions without the need of fine tuning chemical potential.

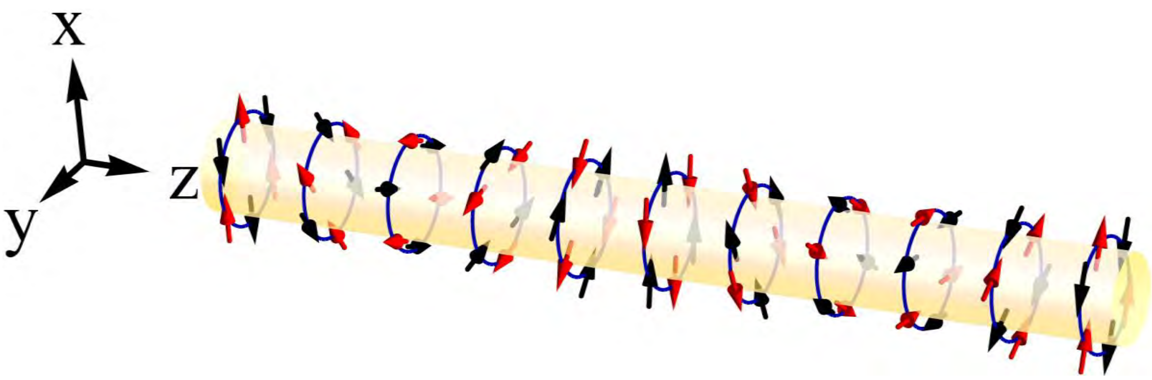

Figure: Illustration of the RKKY-induced anti-ferromagnetic nuclear spin helix in ^{13}C nanotubes. Red and black arrows indicate the nuclear spins on different sublattice sites.

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Topological Aspects of Superfluid ^{3}He Detected by Electrons at Surface

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The *p*-wave superfluid ^{3}He is a textbook example of topological superfluids. Owing to the large degrees of freedom associated with the *p*-wave order parameter, the superfluid ^{3}He exhibits many exotic topological phenomena. Here we present investigations of topological aspects of the superfluid ^{3}He by transport of an electron (electron bubble) trapped below a free surface of the A and B phases of the superfluid ^{3}He.

The A phase (^{3}He-A) is a chiral *p*-wave superfluid with broken time-reversal symmetry (TRS). This phase is also recognized as a superfluid counterpart of a Wyle semimetal recently. In this phase, all Cooper pairs condense into a same orbital angular momentum state, breaking TRS. Direct demonstration of TRS breaking is challenging. We directly demonstrate TRS breaking for the first time by discovering the unusual intrinsic Magnus force acting on an electron moving in ^{3}He-A (Fig. 1)[1], which arises from the nontrivial topology in the order parameter associated with the broken TRS[2].

In the B phase (^{3}He-B), which is a time-reversal invariant topological superfluid, the nontrivial topology generates surface Andreev bound states (SABSs) at a surface. The SABSs should show unusual Majorana nature; their antiparticle is identical to their own particle. To detect the SABSs, we carry out mobility measurements of electrons trapped below a free surface (Fig. 2). We found that the mobility is smaller than that in bulk ^{3}He and that the mobility shows no depth dependence even if the depth is changed over the coherence length[3]. Our recent theoretical calculation qualitatively agrees with the experimental mobility, suggesting the presence of the SABSs at the surface.

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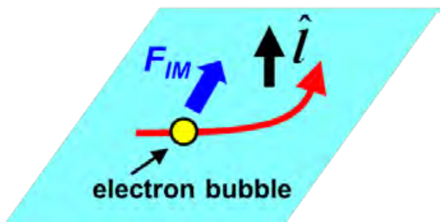

Fig.1. The intrinsic Magnus force.

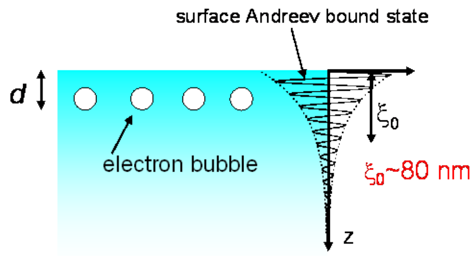

Fig.2. SABSs and electrons below free surface.

Single microwave-photon detector using an impedance-matched Λ system

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Quantum optics in the microwave domain has been developed in the study of circuit quantum electrodynamics (cQED) where the coherent and strong interaction of a superconducting artificial atom with a single microwave photon is realized [1]. Compared to the conventional quantum optics in the optical domain, one missing ingredient in the microwave quantum optics is a high-efficiency single-photon detector. Energy of a microwave photon is four or five orders of magnitude less than that of an optical photon, which makes efficient detection of microwave photons extremely difficult.

In this presentation, we demonstrate practical and efficient detection of an itinerant photon in microwave domain by means of the deterministic switching in an artificial Λ-type three-level system implemented in the dressed states of a driven cQED system where a superconducting flux qubit is coupled to a microwave resonator dispersively [2,3]. In our experiment, resonant microwave pulses with an average photon number of ~ 0.1 are input to the Λ system, and the qubit state after each pulse is immediately read out by using a parametric phase-locked oscillator [4], which enables a fast readout. The photon detection efficiency of (66 ± 6) % has been attained. The loss of the efficiency is mainly attributed to the relaxation of the qubit state due to its short T_1.

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Synchronization of van der Pol oscillators in the quantum regime

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We study the synchronization of coupled mechanical oscillators in the quantum regime. While synchronization phenomena are ubiquitous in nature and have been well studied in the classical theory, its quantum theory has just started to draw attention due to the recent development of optomechanical control techniques of nonlinear mechanical oscillators in the low-excitation regime.

In this work we first perform a phase-space analysis of the steady-state limit cycle by solving a master equation of a quantum van der Pol (vdP) oscillator. We then derive a master equation of a pair of dissipatively-coupled vdP oscillators from a concrete system-environment model. In order to characterize the phase synchronization of two oscillators, we employ the mutual information [Fig.1] and reduced Wigner function as a function of the relative phase of two oscillators [Fig.2]. We found that the qualitative behaviors of the phase entrainment in the quantum regime well agree with those in the classical theory, provided that the phase diagram includes quantum fluctuations around the classical boundaries.

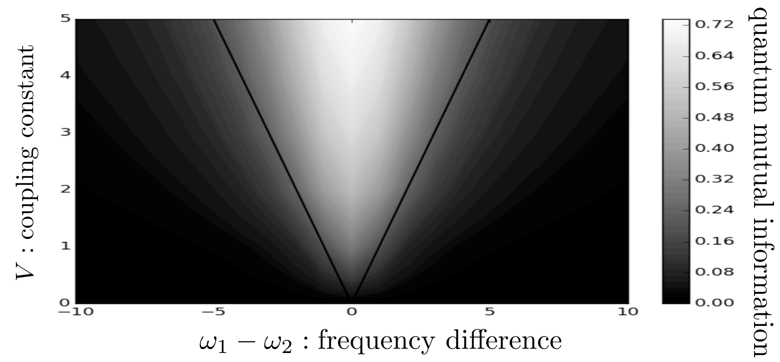

Fig 1. Quantum mutual information
Solid lines ($V=\pm(\omega_1-\omega_2)$) are classical boundaries between synchronized-unsynchronized regime

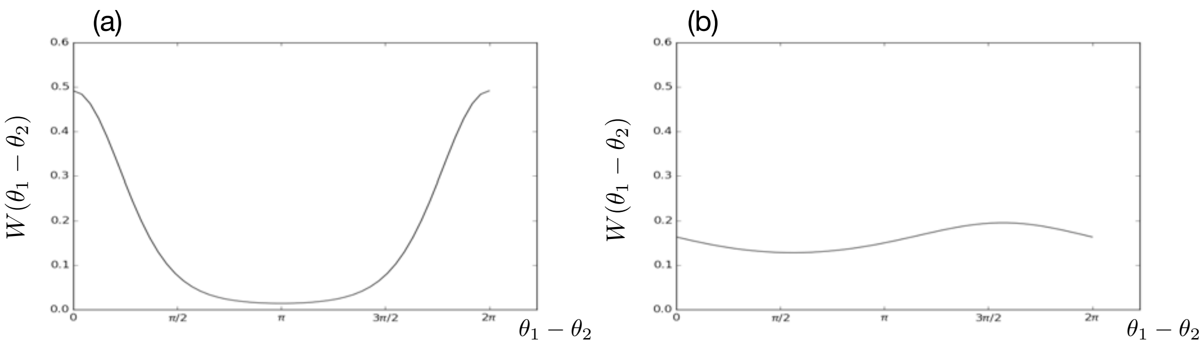

Fig 2. Wigner function vs relative phase
(a) $V=4$, $\omega_1-\omega_2=0$ (b) $V=2$, $\omega_1-\omega_2=8$

Time-bin photon generation using superconducting circuits

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High-efficient quantum state transfer between spatially separated quantum systems is an important challenge and widely investigated toward the development of quantum information network. Coupling between the distant qubits through a localized photon is widely studied in the field of quantum electrodynamics based on superconducting circuits (circuit QED) [1-2], and recent progresses render such technique a common module for quantum information processing utilizing superconducting qubits (SC qubits). Furthermore, an itinerant photon regarded as an ideal information carrier over large distances also becomes more attractive due to recent development [3-7].

An itinerant photonic qubit can be categorized into two groups. One is based on a single mode such as Fock states, called a single-rail qubit. The other, called a dual-rail qubit, utilizes two modes of the itinerant photon such as polarization, path, frequency and time-bin modes. Although generation of the former photonic qubit [3-4] and entanglement between the single-rail and a SC qubit [5] have been successfully demonstrated in the field of the circuit QED, the single-rail photon is known for its vulnerability against photon losses. Therefore, we focus on the dual-rail qubit possessing robustness against photon losses for high-efficient quantum state transfer between two qubits. We are investigating a use of time-bin qubits as dual-rail photonic qubits thorough superconducting circuits. Utilizing entanglement between two SC qubits in a resonator, we generate a time-bin qubit reflecting on the coefficients of the entanglement. We show our simulation results, and discuss how accurately a desired time-bin qubit is emitted.

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Visibility enhancement by a quantum multi readout

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High-fidelity quantum measurements are essential for quantum information processing. Especially, to implement quantum error collection, ancillary qubit state should be accurately readout, and fast feedback control depending on the readout results are necessary [1]. Unless the quantum measurements are reliable, we cannot correct the errors on the qubit. So, we should construct a scheme to realize high-visibility readout. Here, we propose and demonstrate a new way to enhance a visibility for qubit readout. Ideal measurements project qubit states into eigenstate, and the detector shows signal depending on the projected qubit state. However, the detector sometimes shows wrong results due to noise, which we call a detection error. This error suppresses the visibility of quantum measurements. Our proposal to enhance the visibility is based on a majority vote. When we measure the qubit many times, the qubit stays in an initial projected state if the projection occurs accurately, and we get a list of measurement values. By adopting the majority vote of the measurement results, we can readout the state more accurately.

We use a superconducting flux qubit and Josephson bifurcation amplifier (JBA) [3] readout system to demonstrate our method. The JBA readout method is known as a low backaction readout [4]. Also, we show that the projection occurs accurately if we use this JBA readout [2]. We apply qubit resonant pulses to prepare an arbitral qubit-state and readout the qubit state seven times. By using the multi readout, we can enhance visibility from 18.2% to 38.1%.

Our method is general, and so works for any systems as long as the readout keeps the post measurement state. So, if we apply this method to a system with a higher visibility readout, it is possible to realize reliable quantum readout for quantum error collection.

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Bayesian estimation of nuclear-spin bath for adaptive feedback with a single-electron spin qubit

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Spin coherence of confined electrons in a GaAs quantum dot is hindered by the magnetic fluctuation of the nuclear bath. This is because an electron spin is coupled with an ensemble of thermally fluctuating nuclear spins ($\sim 10^6$) through the hyperfine interaction. In a semiclassical description, this effect is treated as fluctuation of the effective magnetic field known as Overhauser field. Since this Overhauser field fluctuates rather slowly, with correlation time ranging from milliseconds to seconds, the fluctuation can be kept track of in real time as previously demonstrated using the precession of a Singlet-Triplet (S-T) qubit and Bayesian estimation. By adaptive control against the estimated Overhauser field, enhancement of the S-T qubit coherent time (T_2^*) from 10 ns to over 2 μs has been realized[1]. This adaptive feedback can also be applied to a single-spin qubit, however, the scheme of real-time estimation of the fluctuating Overhauser field is not established.

Here we investigate a method to use Ramsey fringe of a single-spin qubit to estimate the fluctuating Overhauser field. We simulate the performance of the real-time estimation for a single-spin qubit, and compare it with that for a S-T qubit. First we show that the real-time estimation works well when the Rabi frequency is larger than half the detuning in the Ramsey sequence. Secondly we find that a mean square error of the real-time estimation decreases exponentially as the number of measurements increases. This exponential decrease means that the Bayesian approach for single-spin qubits is as effective as for S-T qubits[2]. Our results predict that the Bayesian estimation using the Ramsey sequence can enhance the coherence time from nanoseconds to microseconds for single-spin qubits.

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NMR system for studying phase decoherence

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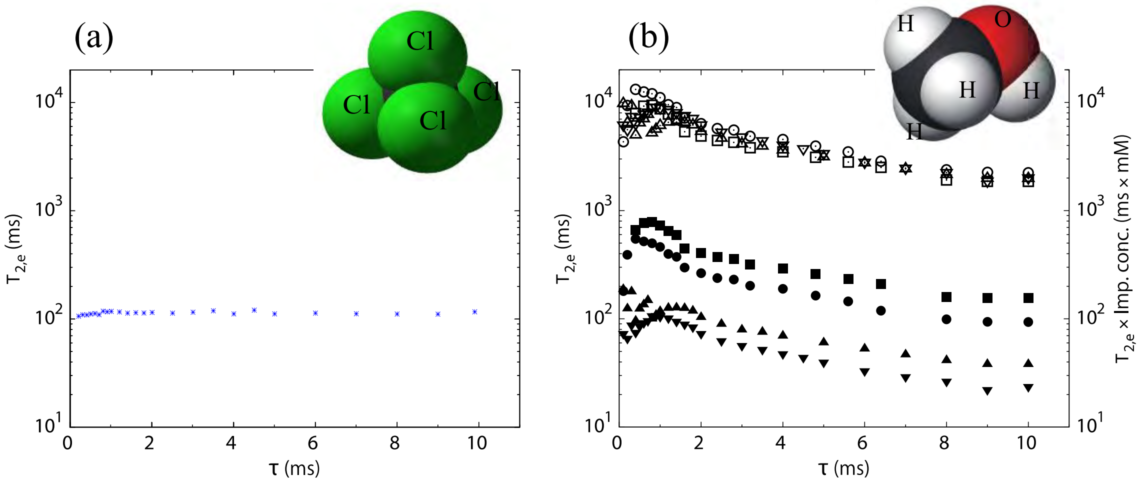
The largest obstacle against realization of quantum computers is decoherence of a system. In order to examine various decoherence suppression techniques, we implement a model system that shows a quadratic decay in the early stage of phase decoherence. This quadratic decay is necessary for these suppression techniques to be effective.

We introduce a magnetic impurity, Fe(III) acac, in the liquid sample. The interaction of a spin with the magnetic impurity is a delta-function-like in time, and thus we do not expect a quadratic decay of the spin state and thus the bang-bang control is not effective, as shown in the figure (a). However, it is not the case for a two-spin molecule. We assume 1) one of the two spins (called E) is under the influence of a magnetic impurity and interacts with the other spin (called S) through a scalar coupling and 2) the spin S interacts only with the spin E and free from the magnetic impurity. The delta function-like interaction on the spin E due to the magnetic impurity is transformed into a slower interaction on the spin S by the scalar coupling. In such a two-spin molecule, the bang-bang control is effective, as shown in the figure (b).

We obtained the model system with which various decoherence suppression techniques, such as Bang-Bang control or Quantum Zeno effect, are examined.



Effective $T_{2,e}$ of ^{13}C in (a) CCl_4 and (b) CH_3OH as a function of a pulse interval τ of Bang-Bang control. Fe(III) acac concentrations are (a) 33 mM and (b) ■ 12 mM, ● 24 mM, ▲ 52 mM, and ▼ 85 mM. Open symbols are $T_{2,e}$ x Impurity concentration in order to normalize the effect of the magnetic impurity.

Quantum non-demolition detection of an itinerant single photon using a superconducting qubit

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Superconducting qubits have been successfully applied in many experiments on microwave quantum optics. Because of their large electric/magnetic dipole moments, they can strongly couple with microwave photons. Accordingly, a number of intriguing phenomena and techniques have been demonstrated, especially in the strong dispersive regime which is rarely achieved in other physical systems [1-3]. However, in most of the experiments, photons confined in a high-quality cavity are treated, because photons in a cavity can be manipulated and measured with superconducting qubits relatively easily. On the other hand, to control and to detect photons in a propagating mode are also essential techniques to realize quantum networks and quantum communication. However, it remains a challenging task to efficiently couple superconducting qubits and photons in a propagating mode. Here, we propose a new scheme for generating entanglement between them. Furthermore, we realize quantum non-demolition detection of an itinerant single photon using a superconducting qubit.

In the experiment, we use a superconducting qubit coupled to a 3D microwave cavity. In the regime where the resonant frequency of the qubit is far from the cavity frequency, they couple with each other dispersively. When a resonant microwave pulse propagating through a waveguide is reflected by the resonator, the photon field interacts with the qubit dispersively through the cavity. If the input state of the microwave pulse contains a single photon, the qubit acquires a phase shift. With a proper tuning of the experimental parameters, the phase shift per photon can be adjusted to π, resulting in a phase-flip of the qubit. After the interaction, we detect the phase-flip of the qubit with a single-shot projective measurement of the qubit and find whether a photon has been reflected or not.

In this work, we use a weak coherent pulse for the input state and measure the detection efficiency. To verify the quantum non-demolitioness, we perform quantum state tomography of the propagating mode after the quantum non-demolition measurement. Homodyne measurements using a degenerate Josephson parametric amplifier and conditioned on the result of the qubit phase-flip allow observation of the non-classical feature of the output mode.

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Theory of microwave single-photon detection using an impedance-matched Λ system

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In circuit quantum-electro-dynamics (QED) systems, we can observe novel quantum optical phenomena that have not been reached by quantum optics in the visible domain. However, efficient detection of propagating single microwave photons has been a long-standing problem in this field. Several schemes have been proposed to date for implementing a single-photon detector. For example, in a recent experiment [1], it was demonstrated that a current-biased Josephson junction tunnels into the finite-voltage state upon arrival of a single microwave photon and thus works as a detector. However, the dark counts and the long dead time after detection are inevitable with this detector.

In this paper, we theoretically discuss a detector based on an “impedance-matched” Λ system [2]. We consider a device in which a qubit and resonator are coupled in the strong dispersive regime and the qubit is driven by an external microwave. Under a proper dive condition, the dressed states of this qubit-resonator system forms an impedance-matched Λ system, where a resonant single photon deterministically induces a Raman transition and excites the qubit [3,4]. Combining this effect and a fast dispersive readout of the qubit [5], we realize a detector of itinerant microwave photons. The present detector achieves a high detection efficiency without relying on precise temporal control of the input pulse shape. The detector can also be reset quickly by applying microwave pulses, which allows a short dead time and a high repetition rate. We also discuss a device in which a qubit is coupled to two resonators, with which we can perform continuous detection of microwave photons.

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Bistable Photon Emission in Hybrid-QED

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We study the photon emission from a voltage-biased double quantum dot coupled to a microwave cavity [1]. We predict that the resulting photonic statistics exhibit a dynamic bistability, which we validate by showing that the distribution describing these statistics has the shape of a tilted ellipse. The switching rates which describe the bistability can be extracted from the electrical current and the shot noise in the quantum dots, and used to predict this elliptic form of the photonic distribution. Our results may be useful for more deeply characterizing the single-atom lasers based on gate-defined quantum dots as the gain medium [2,3].

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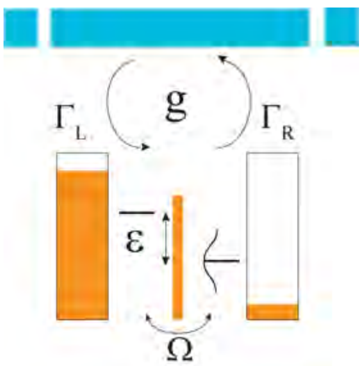

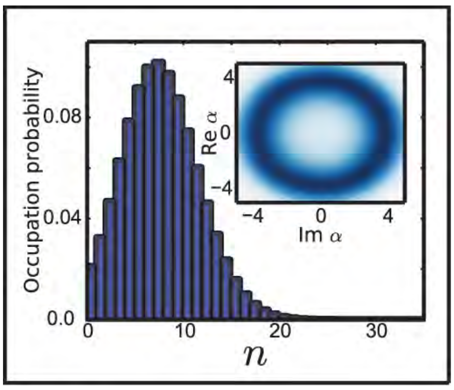

Left: A schematic layout of a double quantum dot coupled to a microwave transmission line cavity. **Right:** An example of a lasing state in the cavity, characterized by a large number of photons and a ring-like Wigner function (inset).

Cavity QED with ferromagnetic magnons in a small YIG sphere

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Hybridizing collective spin excitations in ferromagnetic crystals and a cavity with high cooperativity provides a new research subject in the field of cavity quantum electrodynamics and can also have potential applications to quantum information. In contrast to spin ensembles based on dilute paramagnetic impurities, these spins are strongly exchange-coupled and have a much higher density. Here we report a direct observation of the strong coupling between magnons and microwave photons at both cryogenic and room temperatures by using the same small yttrium-iron-garnet (YIG) ferromagnetic sphere in a 3D copper cavity. We observed strong couplings of the same cavity mode to both ferromagnetic-resonance (FMR, uniform precession) mode and a magnetostatic (MS, non-uniform precession) mode in the quantum limit at 22 mK. Then, at room temperature, we observed a strong coupling of the cavity mode to the FMR mode with slightly increased damping rate. This reveals the robustness of the FMR mode against temperature. However, the coupling to MS mode disappears at room temperature and numerically simulations show that this is due to a drastic increase of the damping rate of the MS mode. Our work unveils quantum-coherence properties of the magnons at both cryogenic and room temperatures.

Interplay of chiral anomaly and particle hole asymmetry on the magneto-optical conductivity of Weyl semimetals

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Weyl semimetals are three-dimensional analogs of graphene. One of the main exotic property of this material is chiral anomaly which suggests a non-conservation law of particle number of left and right handed Dirac fermions. Recently Weyl semimetals has been verified in experiments related to both real materials (e.g. TaAs) and artificial systems (e.g. photonic crystals). In this poster I will show recent analytical results on the magneto-optical conductivity of Weyl semimetals. In a specific material like Cd3As2, obvious breaking of particle-hole symmetry will bring non-relativistic effects to the three dimensional Dirac fermions in this material. We have found in the magneto-optical conductivity, one absorption peak will split into two corresponding to left and right circular polarized light separately. However the Berry curvature is not changed by the particle-hole asymmetry. The conductivity along the z-direction which is parallel to the electric and magnetic field will also be discussed.

Josephson Parametric Amplifier and Oscillator and their Application to Quantum Information Processing

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Josephson parametric amplifier (JPA) has become an important resource for superconducting quantum information experiments. We incorporated a flux-driven JPA [1] as a preamplifier in our setup for the dispersive readout of superconducting qubits. This led to drastic improvement in the signal to noise ratio and enabled us to achieve single-shot readout and observation of quantum jumps [2].

The same circuit of the flux-driven JPA can also work as a parametric phase-locked oscillator (PPLO) at the pump power above the oscillation threshold. Using a PPLO, we demonstrated the demodulation of a microwave signal of the order of a femtowatt digitally modulated by binary phase-shift keying. We apply this demodulation capability to discriminate the qubit-state-dependent phase shift in the probe microwave field reflected from a resonator coupled to a qubit. The scheme offers a fast, high-fidelity, and non-destructive readout [3]. The developed qubit-readout technique can be applied to detection of single-microwave photon [4].

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Controlling entanglement of spin qubits in a triple quantum dot

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Entanglement is the fundamental resource for the quantum information processing. In semiconductor-based quantum dot architecture, entanglement of electron spins is readily controlled by gate-tunable exchange coupling[1]. It has been employed in entangling nearest neighbor electron spins[2,3], but scalability of this architecture has remained questionable because the third spin added to two-spin systems tends to be either isolated or lacking addressability so far.

In this poster, we demonstrate the generation of both locally and nonlocally entangled qubit pairs with a simple pulse sequence under fully tunable exchange coupling in a triple quantum dot (TQD), while maintaining addressability of each qubit. We observe coherent oscillations between singlet and triplet states formed in either nearest neighbor or next-nearest neighbor quantum dots. The accurate control of the exchange coupling in the TQD is realized based on three-spin state spectroscopy from which we can derive all the relevant TQD parameters. This result also enables us to realize single-qubit Rabi rotations and two-qubit SWAP gate operations which constitute the universal set of gate operations in a triple qubit system.

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Single-ion spectroscopy of rare-earth ions contained in an inorganic crystal at cryogenic temperature

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In the context of modern solid-state spectroscopy, rare-earth (RE) ions contained in an inorganic crystal have been recognized as an attractive, yet formidable target over three decades. RE ions have forbidden optical transitions between two 4*f* electronic configurations with a long radiation lifetime reaching to 100 μs. The hyperfine splitting about 10 MHz due to the nuclear spin appears on the spectral line of a single RE ion, whose linewidth narrows down to 10 kHz of its lifetime-limited width at a few K. The single nuclear spin quantum state can be determined by measuring the optical transition frequency of the ion. However, the optical detection of a single RE ion is extremely difficult due to its weak photo-luminescence. The long lifetime of the excited 4*f* state inevitably results in the poor spontaneous emission rate lower about three orders of magnitude than that of typical organic dye molecules, which have already been observed by the cryogenic single-molecule spectroscopy.

We have consulted on the low temperature spectroscopy of a single praseodymium ion doped in a bulk lanthanum trifluoride crystal (Pr^{3+}:LaF_3) [1]. The experiment was carried by a homemade cryogenic setup using a newly developed high-NA objective [2]. The confocal reflecting microscope had the detection efficiency up to 0.43%. To resolve the narrow absorption line of a single Pr^{3+}, the linewidth of the lightsource was made narrower than 0.4 MHz by employing a ULE optical cavity. Spectral lines of the $^3H_4 \rightarrow {}^3P_0$ transition of individual Pr^{3+} ions were resolved as luminescence peaks with intensities of 20-30 cps and the full-width at half-maximum of approximately 3 MHz at 1.5K. The population transfer of a single Pr nuclear spin was demonstrated via the optical pumping process of the ion.

I.N. was financially supported by GCOE program on "Nano Science and Quantum Physics" in Tokyo Institute of Technology.

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Toward frequency-domain quantum computation using a monolithic cavity of rare-earth-ion-doped crystal

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The rare-earth-ion-doped crystal, such as Pr^{3+}: Y_2SiO_5, is a promising material for quantum information devices, because the crystal contains many ions whose nuclear-spin states have long coherence time. Frequency-domain quantum computation (FDQC) allows us to employ many ions as qubits without identification of their positions [1]. In the FDQC, ions employed as qubits are coupled to a cavity mode of a monolithic cavity which is made by the crystal (Fig. 1). Although operation light is irradiated to the whole system including ions which are not intended to operate, a certain ion which are resonant with the operation light can be selectively manipulated, because each ion has its own specific transition frequencies [1,2].

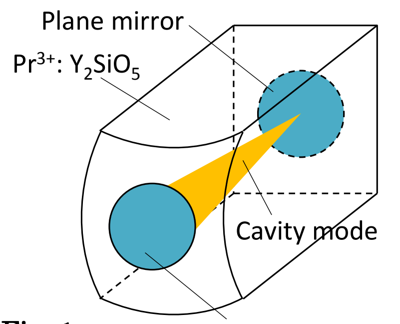

Fig. 1

Strong coupling between ions and the cavity mode is required to perform high-fidelity gate in the FDQC. Therefore, the cavity is required to have low loss and small mode volume. We investigate the loss of the cavity for loss reduction, and find that the loss depends on polarization of the mode [3]. We find also that the dependence is caused by polarization dependence of inter-mode coupling in the cavity. When the lowest mode is observed by scanning frequency of incident laser, some higher mode is observed simultaneously with the lowest mode (Fig. 2). The ratio of the higher mode to the lowest mode is Lorentzian. It means that the higher mode is excited by coupling to the lowest mode. We will show that the coupling causes loss of the cavity, and discuss how to reduce the loss.

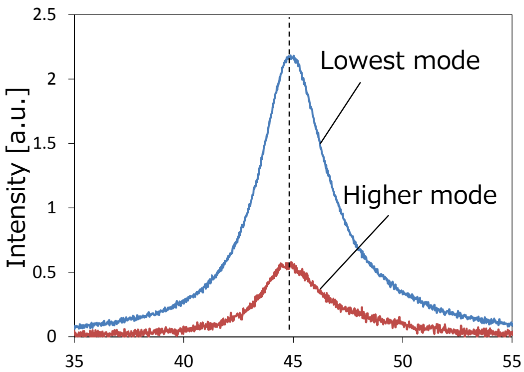

Fig. 2

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Dynamics of surface state electrons on liquid helium exposed to microwave intersubband excitation and quantizing magnetic field

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Previously magnetoconductity oscillations and vanishing of magnetoresistance in a two-dimensional (2D) electron system on liquid helium exposed to a resonant microwave irradiation were observed[1]. Zero-resistance state (ZRS) concurs with nonequilibrium spatial redistribution of the 2D electrons from the center to the edge of the electron spot[2] and excitation of self-generated oscillations (SGO) of the charge density[3].

Here we present the results of a further experimental study of SGO of surface state electrons on liquid helium. We use the Corbino geometry cell with one of ring electrodes divided into 4 segments (see fig.1) and measure ac transient current for each segment. Cross-correlation function analysis of obtained data shows a phase shift between current oscillations for different segments that implies existence of circular charge flow within the electron pool. The charge flow changes its direction when a polarity of the magnetic field is changed.

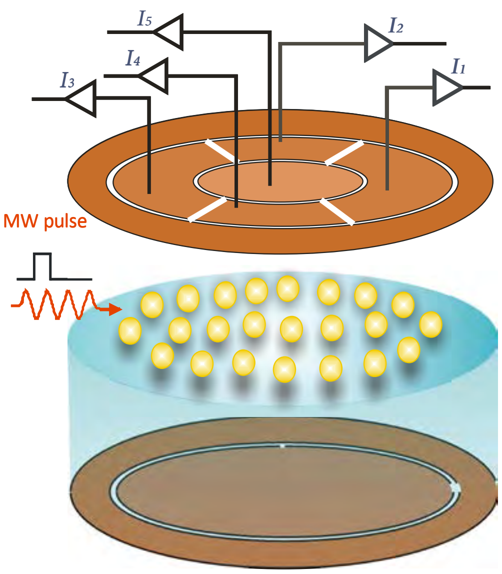

Fig.1 The experimental cell.

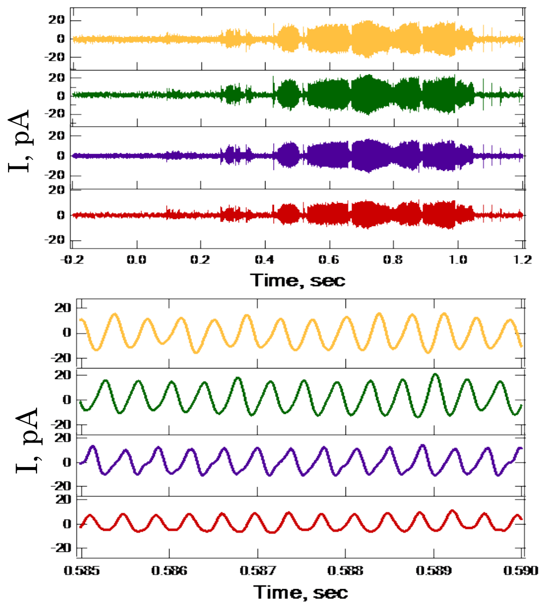

Fig.2 AC transient current under ZRS conditions.

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Electromechanical system using a Si_3N_4 membrane inside a 3D microwave cavity

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A quantum world is opening up for massive objects; quantum ground-state cooling [1] and quantum-state manipulation [2] of massive objects have been demonstrated recently in the field of electro-(opto-) mechanics. Now, it is widely recognized that electromagnetic fields allow measurement and control of the mechanical oscillations of massive objects even in the quantum regime. Many other kinds of massive quantum 'mechanical' systems are also being investigated [3].

We construct an electromechanical system with a parallel-plate capacitor embedded in a 3D cavity. The capacitor is galvanically connected to the body of the cavity, comprising a microwave LC resonator. The vacuum-gap capacitor consists of an Al electrode evaporated on a Si_3N_4 membrane and counter electrodes separated by 300 nm. The membrane supports high-quality mechanical oscillation modes. The oscillations of the membrane modulate the capacitance in the circuit and thus its resonant frequency, leading to electromechanical coupling.

In the electromechanical system, microwave photons of the resonator mode and phonons of the membrane oscillation mode are parametrically coupled via a pump microwave field. Using this interaction, we demonstrate a "microwave-induced cooling" of the membrane reaching near the quantum ground state. We also demonstrate parametric coupling between two oscillation modes of the membrane via the microwave resonator mode under two-tone pump microwaves. This coupling strength is larger than the decay rates of each mechanical mode, and a "strong coupling regime" of phonon modes is achieved.

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Coherent electron-spin-resonance control of three individual spins in a triple quantum dot

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Multiple quantum dots (QDs) are fascinating systems to explore the physics of electron interactions. The confined electron spins in QDs can be addressed both electrically and optically, which makes QDs highly promising building blocks for quantum information processing [1]. Recent experiments on GaAs QDs have demonstrated the key ingredients of quantum computation, such as single-spin rotations by electron spin resonance (ESR) [2] and pulsed control of spin-spin interaction [3]. Fast single-spin manipulation (with fidelity up to 96%) was achieved [4] by employing a magnetic field gradient induced by a specially designed micro-magnet (MM). The number of qubits, however, has so far been limited to two. The next step to implement quantum algorithms is to scale up this system to three or more.

In this presentation, we will demonstrate initialization, control and readout of three single spins in a laterally coupled triple QD based on GaAs defined by gate electrodes. Initialization and detection of spin state is performed by pulse operation of detuning energies between two adjacent QDs. Each spin state can be manipulated individually by frequency-selective ESR with a maximum Rabi frequency up to 25MHz. The spin in the right QD shows the largest Rabi frequency in agreement with the simulated local magnetic field property created by the MM. This individual control over three spins enables us to arbitrarily change the magnetic spin quantum number of the three spin system, and thus to operate a triple-dot device as a three-qubit system in combination with the existing technique of exchange operations among three spins.

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Nobel phenomena of photons in three-dimensional ring-resonator arrays

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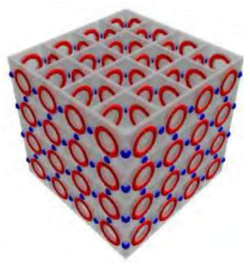
Recently, much attention has been paid to two-dimensional ring-resonator arrays as a platform for topological phenomena, synthetic gauge fields, and many body physics of photons. For instance, photonic helical edge states can be realized in such systems with and without a synthetic magnetic field [1,2]. By introducing two-level atoms in the resonators, a photonic counterpart of the fractional quantum Hall effect can emerge via the photon blockade effect and synthetic magnetic field [3].



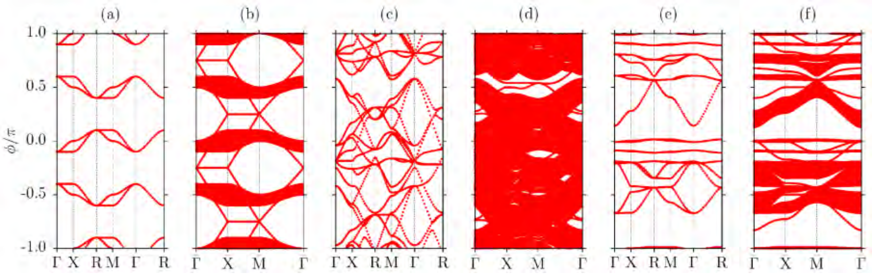


Fig. 1: 3d ring-resonator array. **Fig. 2**: Band structures of the bulk and slab modes.

A three-dimensional ring-resonator array depicted in Fig. 1 is an extension of the 2d one and has various interesting facets in its physics: an optical realization of Chalker-Coddington type network, mapping to a Floquet-Bloch system, higher crystal symmetry with triple degeneracy, and U(1) gauge symmetry. Recently, we have shown that the system can have a gapped bulk band structure and gapless surface states in its quasienergy spectrum as shown in Fig. 2 [4]. There are the bosonic time-reversal symmetry and crystal symmetry of the simple cubic lattice behind the spectrum, having a similarity to topological crystalline insulator. Moreover, via the photon blockade mediated by two-level atoms loaded in the resonators, the system will become an interacting photonic system, similar as those described by the Bose-Hubbard model. This may provide a novel route of quantum simulation via photons.

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Cavity optomagnonics using a whispering gallery mode resonator

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Whispering gallery modes (WGMs) have drawn large attentions and offered a suitable platform for the enhancement of the nonlinear optical phenomena for their small mode volumes and high quality factors. Moreover, in contrast to other resonators such as Fabry-Perot cavities, WGM resonators exhibit the spin-orbit coupling of light, where the angular motion and the polarization of photons are inseparable. Our scope is to utilize the spin-orbit-coupled nature of WGM photons for the selective creation or annihilation of collective spin excitations inside a macroscopic-scale resonator supporting the WGM.

As a WGM resonator, we use a sphere of a ferromagnetic insulator, yttrium iron garnet (YIG), which is transparent at the wavelength of 1.5 µm. The YIG sphere supports a number of ferromagnetic magnetostatic modes including the Kittel mode with spatially uniform spin precessions corresponding to a zero wavevector. The magneto-optical scattering interconnects the WGM photons and the magnons so that the system of cavity optomagnonics emerges. By measuring the optical sideband generated by the magnon-induced Brillouin scattering, we observe the pronounced nonreciprocity and asymmetry of the sideband signals [1]. We find that these observations are the consequences from the spin-orbit-coupled nature of WGM photons and the selection rules of the optical transitions involving ferromagnetic magnons. The unique features of the system may find interesting applications at the crossroad between quantum optics and spintronics.

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Electron spin resonance in a quadruple quantum dot

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Electron spins trapped in quantum dots (QDs) are good candidates of quantum bits for quantum information processing. Basic operations of the qubit have been demonstrated in recent years. The next important step towards realizing larger scale quantum algorithms is scale-up of the system. Here, we realize a quadruple quantum dot (QQD) system and observe electron spin resonance for all four QDs.

We fabricate a QQD device on a GaAs/AlGaAs heterostructure wafer (Fig. (a)). A few-electron QQD is formed by tuning the gate voltages and measured by RF reflectometry. We observe Pauli spin blockade in QD 1 and 2 (3 and 4), which is used to read out spin states of the QQD.

We apply microwave voltages on gate C to induce electrically driven electron spin resonance utilizing an inhomogeneous magnetic field created by a Co micromagnet deposited on the sample. Figure (b) and (c) show the observed electron spin resonance as a function of the microwave frequency and the external magnetic field. Four resonance lines corresponding to the four QDs are observed. These results are important to realize a four qubit system and further scale-up of the system by multiple QDs.

Reference: T. Otsuka *et al.*, arXiv:1510.02547

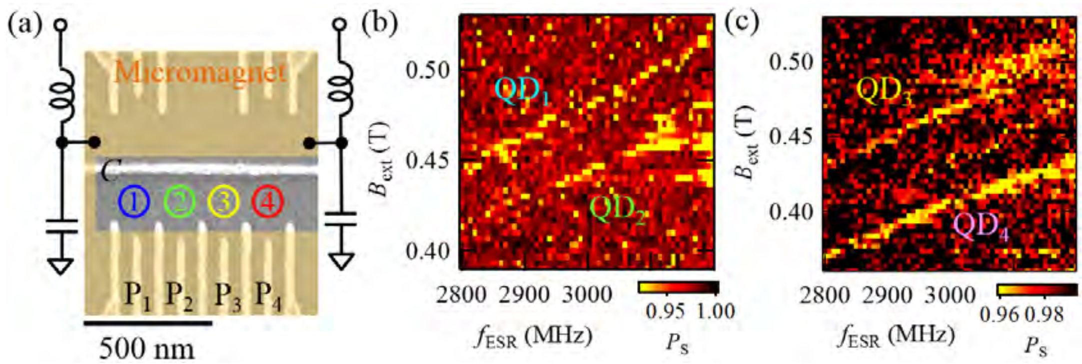

Fig. (a) Scanning electron micrograph of the device and schematic of the measurement setup, (b) ((c)) Observed electron spin resonance in QD 1 and 2 (3 and 4)

Fractional charge in quantum dot arrays with density modulation

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We perform a numerical study of quantum dot arrays subject to charge-density-wave potentials and find that generic rational fractional charges can be realized at the ends of these one-dimensional systems. The fractional charges are understood in the framework of adiabatic pumping. We show that the magnitudes of fractional charges can be tuned by varying the phase of the charge-density-wave potential or the total number of quantum dots in the array. We discuss the minimum system size to observe fractional charges in the experiment.

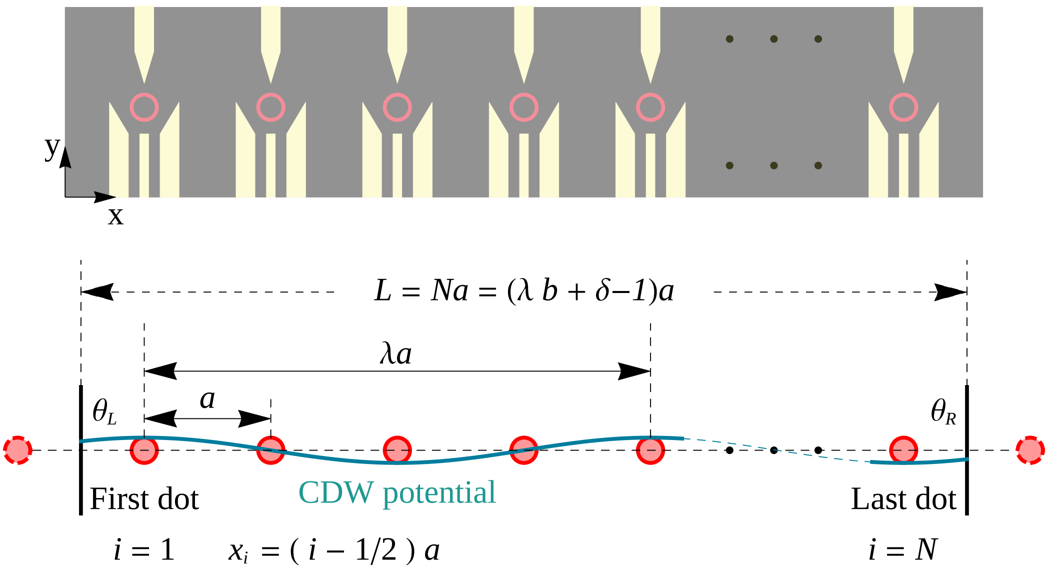

Figure: Schematic view of a setup with charge-density-wave potential.

Controllable single-photon transport between remote coupled-cavity arrays

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We develop a new approach for controllable single-photon transport between two remote quantum registers mediated by a quantum channel. It employs three one-dimensional coupled-cavity arrays to make up the channel and the registers, as shown in Fig. 1(a). A single two-level atom located inside one cavity of the intermediate array is used to control the long-range coherent quantum coupling between two remote registers, thereby functioning as a quantum switch. With a time-independent perturbative treatment, we find that the leakage of quantum information can in principle be made arbitrarily small. Furthermore, our method can be extended to realize a quantum router in multi-register quantum networks, where single-photons can be either stored in one of the registers or transported to another on demand, as depicted in Fig. 1(b). These results are confirmed by numerical simulations.

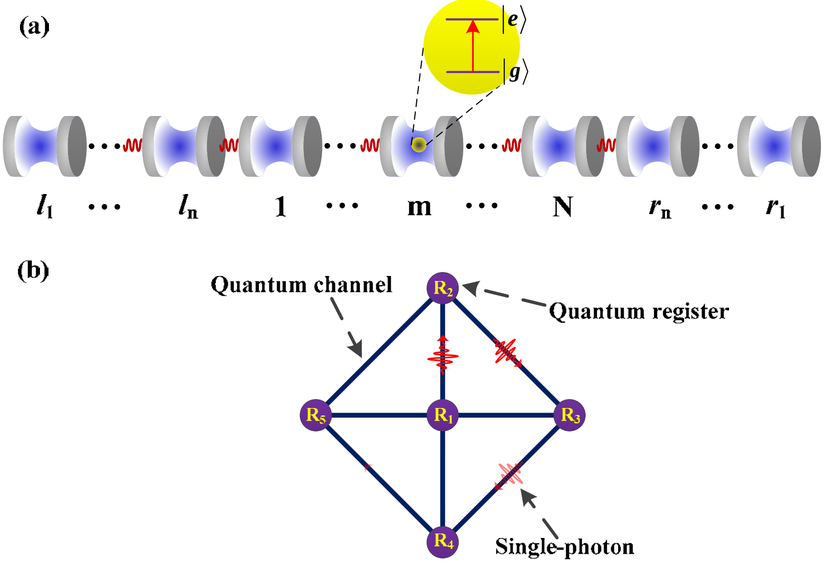

Fig.1. (a) A 1D CCA of having 1 cavities and a two-level atom is employed as a quantum channel to connect two distant quantum registers composed of two identical 1D CCAs, each contains 1 cavities. (b) Schematic illustration of an example network which is made up of five registers and eight channels.

Coherent coupling between a ferromagnetic magnon and a superconducting qubit

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Coherent coupling between spin ensembles and superconducting quantum circuits is now widely studied for quantum memories and microwave-to-optical quantum transducers. Since those applications require strong coupling and sufficiently long coherence times simultaneously, collective spin excitations (magnons) in yttrium iron garnet (YIG), a typical ferromagnetic insulator, are an alternative promising candidate for the media for quantum storage and transduction. The material is known to have a high spin density (2×10^{22} cm^{-3}) and a narrow ferromagnetic resonance linewidth (~45 kHz at 4.2 K [1]). Recently, we achieved strong coupling between a microwave mode in a 3D cavity and the spatially uniform spin-precession mode (Kittel mode) in a YIG crystal [2].

In this poster presentation, we demonstrate coherent coupling between the spin mode excitation in a millimeter-sized ferromagnetic sphere and a superconducting qubit, in which the interaction is mediated by a microwave cavity [3]. The YIG sphere is located at the end of the 5-cm-long cavity, and it interacts with the magnetic field of a cavity mode. The qubit placed at the other end of the cavity, on the other hand, interacts with an electric field of the same cavity mode. With this setup, we observe the coupling strength (8.5 MHz) well exceeding the damping rates (1.1 MHz and 1.6 MHz for the Kittel mode and the qubit, respectively), revealing the qubit-magnon hybrid system in the strong coupling regime. In the time-domain measurement, we selectively excite the Kittel mode and observe the following oscillating time evolution of the qubit state, which is caused by the magnon-qubit interaction. This oscillation clearly indicates the coherent exchange of an energy quantum between the qubit and the Kittel mode. Our approach provides a versatile tool for control and measurement of the magnon excitations in the quantum regime and opens a path toward ferromagnet-based quantum transducers.

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A fast addressable spin qubit in a silicon quantum dot

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Electron spins in silicon quantum dots are one of the promising candidates for implementation of solid state quantum computing because of their long coherence time and scalability. By recent extensive efforts in experiments using few-electron Si quantum dots, it becomes possible to manipulate single spins using a microwave antenna [1] or a micro-magnet [2], although the spin manipulation speed (Rabi frequency) in these measurements (~ MHz) is slower than those obtained for III-V semiconductor quantum dots (~100 MHz) [3,4]. The enhancement of the Rabi frequency is desirable because it increases the possible number of gate operations within the coherence time and thus potentially increases qubit gate fidelities.

In this work, we integrate a Si/SiGe double quantum dot and a micro-magnet with optimized structure to enable fast and addressable single-spin qubit operations. The micro-magnet is designed to maximize the slanting fields for both dots and the local magnetic field difference between the two dots [4].

The measurement of electric dipole spin resonance is performed by applying microwave bursts to a gate electrode. The time resolved measurements show well-defined Rabi oscillations and chevron patterns for each electron spin in the double quantum dot. The maximum Rabi frequency obtained here is about 35 MHz, which is the highest value reported for single-electron spins in silicon [1,2].

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Controlling and Probing non-Abelian Emergent Gauge Potentials in Spinor Bose-Fermi Mixtures

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Gauge fields, typified by the electromagnetic field, often appear as emergent phenomena due to geometrical properties of a curved Hilbert subspace, and provide a key mechanism for understanding such exotic phenomena as the anomalous and topological Hall effects. Non-abelian gauge potentials serve as a source of non-singular magnetic monopoles. Here we show that unlike conventional solid materials, the non-abelianness of emergent gauge potentials in spinor Bose-Fermi atomic mixtures can be continuously varied by changing the relative particle-number densities of bosons and fermions [1]. The non-abelian feature is captured by an explicit dependence of the measurable spin current density of fermions in the mixture on the variable coupling constant. Spinor mixtures also provide us with a method to coherently and spontaneously generate a pure spin current without relying on the spin Hall effect. Such a spin current is expected to have potential applications in the new generation of atomtronic devices.

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Electron paramagnetic resonance spectroscopy using a micrometer-sized dc-SQUID magnetometer directly coupled to an electron spin ensemble

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Electron paramagnetic resonance (EPR) spectroscopy is a widely-used tool for evaluating material properties in vast fields of basic and applied research [1]. Recently, EPR spectroscopy of small number of electron spins (~1700 spins) is demonstrated using a superconducting resonator with a Josephson parametric amplifier toward realizing single spin detection [2].

We demonstrate EPR spectroscopy using a micrometer-sized direct current superconducting quantum interference device (dc-SQUID) magnetometer [3]. The dc-SQUID and an electron spin ensemble are directly glued. In our method, the change in the magnetization induced by EPR is detected by the dc-SQUID rather than the change in microwave absorption in the case of conventional EPR spectrometers using cavities or resonators. As a proof-of-principle experiment of electron spin polarization detection, we measure temperature and magnetic field dependence of the dc-SQUID response using Er:Y_2SiO_5 based electron spin ensemble. The dependence shows clear hyperbolic tangent behavior, which reflects electron spin polarization ratio. We also perform EPR spectroscopy of impurity centers in type Ib HPHT diamond and confirm EPR peaks of P1 centers and NV^- centers. Estimated minimum detectable number of spins and sensing volume of our EPR spectroscopy is ~10^6 and ~10^{-10} (~0.1 pl), respectively.

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Photonic quantum gates using multilevel atomic systems

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We propose the methods for implementing the quantum logic gates between photons, where multilevel atomic systems mediate the interactions between photons. The atomic systems are supposed to be coupled strongly to a one-dimensional waveguide, assisted by the Purcell effect of a cavity if necessary. The proposed methods can work as the SWAP gate between the photonic and atomic qubits, and also work as the controlled-phase gate between consecutively input photons. We also consider the practical implementations using a neutral atom or superconducting qubits. The proposed schemes could be used as the building blocks for universal quantum computation.

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Randomized benchmarking on superconducting qubit and gate fidelity improvement

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Quantum computers are expected to exhibit an exponential speed up against classical computers. On the other hand, when characterizing the time-evolution of a quantum system by implementing quantum process tomography, the number of measurements will explode exponentially as the number of qubits increases. Therefore, in the aim of constructing a large quantum computing system, it is necessary to design a scalable estimation protocol for the performance evaluation.

Randomized Benchmarking (RB) is an experimental protocol to evaluate the average gate fidelity of qubit gates and it is known to be scalable for an increasing number of qubits. In our research, we have conducted RB experiments on a superconducting qubit and used it as a measure to find the optimal parameter for single-qubit gates.

Furthermore, we are investigating the distribution of measured fidelity in the RB experiments so as to extract more information besides the average gate fidelity. We observe an indication of non-Markovian errors in our measurement as suggested in Ref.[1].

In this presentation, we give an introduction to RB protocol and its implementation in superconducting qubit experiments. We also discuss the role of the non-Markovian errors in RB experiments and discuss the validity of current RB protocol.

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Spin orbit interaction in single Ge/Si core/shell nanowires with electrically swinging dual gates

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Ge/Si core/shell nanowires are predicted to possess strong spin-orbit interaction (SOI) and lack nuclear spins making them candidates for fast all electrical spin manipulation and long spin coherence times. Magnetoconductance measurement of weak antilocalization (WAL) effect is a standard method to extract the SOI strength in nanowires since the presence of quantum interference results in a suppression of back scattering and an increase of transport conductance. Previous studies have demonstrated the short spin-orbit length (l_{so}< 25nm) of Ge/Si core/shell nanowires extracted in either extend wire or Coulomb blockade regime under single electrical gating. In this work, a double gating device is fabricated with the goal of investigating the electric field tuning of Rashba type SOI whilst the carrier density (or electron momentum) is maintained. In addition, by superimposing a small alternating signal on the *d.c.* gate bias we find that the universal conductance fluctuations (usually manifested in the quantum transport of low dimensional structures) are dramatically removed from the magnetoconductance background, enabling a better fitting to WAL theory models.

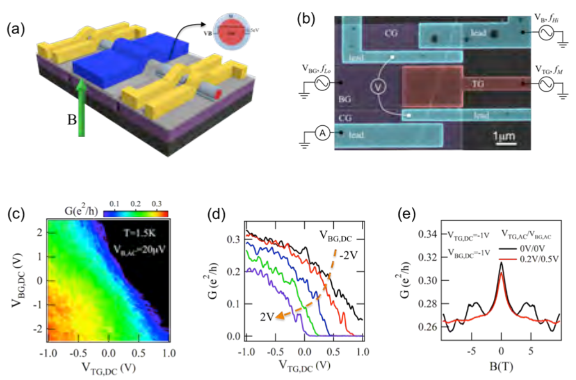

Fig. (a) Scheme and (b) false color scanning electron microscopy (SEM) image of a typical Ge/Si core/shell nanowire device with dual gates and 4-terminals. (c) Conductance G as a function of *d.c.* top gate voltage $V_{TG,DC}$ and back gate voltage $V_{BG,DC}$. Data taken with an *a.c.* excitation of 20μV, 137Hz at a temperature of 1.5K. (d) Conductance as a function of top gate voltage as back gate voltage changes from -2V to 2V(1V/step). (e) Comparison of magnetoconductance as a function of magnetic field B with or without *a.c.* gate voltages.

Tunable electromagnetically induced transparency in a composite superconducting system

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Electromagnetically induced transparency (EIT) has been demonstrated in various artificial systems[1,2,3,4]. However, EIT in superconducting systems is more fragile due to relatively short coherence times[4]. We theoretically propose an efficient method to realize EIT in the microwave regime in a composite system consisting of a flux qubit and a superconducting LC resonator. Driven by two appropriate microwave fields, the system will be trapped into dark states. Two absorptive transitions have equal probability amplitudes but opposite signs, leading to destructive quantum interference, and this composite system becomes transparent to the probe field. In our proposal, a second-order transfer plays the role of control field for EIT rather than a direct strong-pump field. In particular, we obtain conditions for EIT and Autler-Townes splitting in this composite system[3,4]. Both theoretical and numerical results show that this EIT system benefits from the relatively long coherent time of the resonator. Since this whole system is artificial and tunable, our scheme may have potential applications in various fields.

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Quantum Computation using Spin-Vortex Induced Loop Currents as qubits

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We propose new theory of cuprate superconductivity based on Spin-Vortex Induced Loop Currents(SVILC)[1]. At extreme low temperature, holes lose their mobility by the distortion of lattice. This makes spin of each electron around the holes spin-vortex. Then the energy of CuO_2 plane is lower if persistent currents are induced. This is Spin-Vortex Induced Loop Current. This currents are derived from single-valued requirement of wave function. And they have a degree of freedom about loop direction governed by the winding number of χ. So, this currents are available for qubits of quantum computer. By the result of Monte-Carlo simulation, cooling CuO_2 plane of cuprate under the pointed electric potential can make stable spin vortex at will. And, stable unit SVILC flows is Single-Vortex-Quartet(SVQ)(Fig. 1). Around this structure, 16 patterns of currents can be flown by the winding number of χ. But, only 8 patterns of them are available for qubits because they are topologically stable.

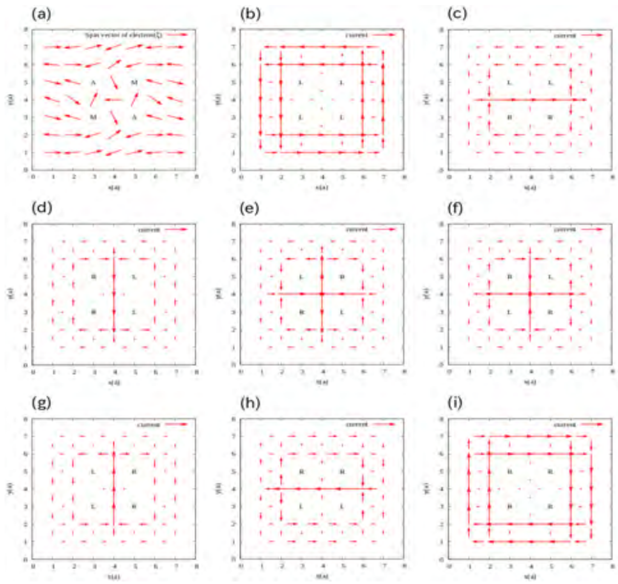

Fig. 1 The spin structure of SVQ and 8 current patterns available for qubits. These 8 states are derived applying tilted Magnetic field ΔB=(0.1,0.5,0) (T/nm). The lattice constant is a = 0.4(nm).
(a) The spin structure of SVQ. Four spin vortices are coupled. M and A indicate the winding numbers of ξ are +1 and -1, respectively. Then ξ is azimuth angle of each electrons' spin.
(b)-(i) The patterns of SVILCs illustrated by red arrow. L and R indicate the winding numbers of χ are +1 and -1, respectively.

Between each states there are electric dipole transition moment. So, by irradiating laser to the energy difference between given two states superpositioned state can be controlled of them. In addition, some dipole moments are larger tha that between 1s and 2p orbitals of H atom. So, SVILC qubit is easy to fabricate and characteristics as qubit are very promising. We will introduce how to fabricate each single qubit for SVILC qubits and the mechanisms of decoherence of this qubit[2].

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Experimental Observing Non-Markovianity of Quantum Evolution with Entanglement in Solid State System

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The dynamics of an ideal Markovian open quantum systems is of the characteristics that the noise from the surroundings acts the same way all the time, and the information of system leaks into the environment unidirectionally. However, the dynamics of realistic open quantum systems can be a non-Markovian process, where information can flow back from the environment into the system. Here we quantify the non-Markovian character of the quantum evolution with entanglement for the diamond-based solid state system. We observe the non-Markovian characteristics of the entanglement evolution under dynamical decoupling and obtain the degree of non-Markovianity of the quantum evolution in diamond, from which we gain some knowledge of the real environment. This method is potentially useful to quantum information processing and quantum metrology.

Opto-Electromechanics for Quantum Transducer

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Stimulated by a recent first commercial quantum annealing machine and a demonstration of quantum error correction code, a rapid progress towards the development of large scale quantum information processing using superconducting circuits is taking place. Along with these developments, numerous efforts have taken place to couple the circuits to other quantum systems to further enhance its performance and utilities. Recent technological advancement in MEMS/NEMS (Micro/Nano Electro Mechanical Systems) has enabled an exploration of phononic degree of freedom to be coupled to superconducting circuits. Stationary localized phonon, using flexural mode of a thin aluminum drum coupled to a microwave resonator has been laser cooled to its ground state [1]. Strong coupling of stationary mode to a qubit has also been shown in the same system, as well as using a piezo electric material [2]. Recently, other type of phononic mode using a traveling surface acoustic mode (SAW) have also been utilized for coupling to a qubit [3]. Besides the investigations in the microwave regime, nanomechanical systems in optical regime, optomechanics, are also in progress, including a demonstration of ground state cooling [4].

We are currently investigating the hybridization of these nanomechanical systems in both microwave and optical regime for the realization of quantum transducer. A coherent transduction between microwave and optical photon is important infrastructure for the development of quantum information network, where the quantum information processors are networked through optical quantum channels. We present the current progress of the development of opto-eletctromechanical system using Si_3N_4 membrane flexural mode.

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Long-distance entanglement of spin qubits via quantum Hall edge states

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The implementation of a functional quantum computer involves entangling and coherent manipulation of a large number of qubits. For qubits based on electron spins confined in quantum dots, which are among the most investigated solid-state qubits at present, architectural challenges are often encountered in the design of quantum circuits attempting to assemble the qubits within the very limited space available. Here, we provide a solution to such challenges based on an approach to realizing entanglement of spin qubits over long distances. We show that long-range Ruderman-Kittel-Kasuya-Yosida interaction of confined electron spins can be established by quantum Hall edge states, leading to an exchange coupling of spin qubits. The coupling is anisotropic and can be either Ising-type or XY-type, depending on the spin polarization of the edge state. Such a property, combined with the dependence of the electron-spin susceptibility on the chirality of the edge state, can be utilized to gain valuable insights into the topological nature of various quantum Hall states.

Coherent manipulation of a Majorana qubit by a mechanical resonator

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We propose [1] a hybrid system composed of a Majorana qubit and a nanomechanical resonator, implemented by a spin-orbit-coupled superconducting nanowire, using a set of static and oscillating ferromagnetic (FM) gates (as schematically shown in Fig. 1). The FM gates induce Majorana bound states in the nanowire, which hybridize and constitute a Majorana qubit. Due to the oscillation of one of these gates, the Majorana qubit can be coherently rotated. By tuning the gate voltage to modulate the local spin-orbit coupling, it is possible to reach the resonance of the qubit-oscillator system for relatively strong couplings.

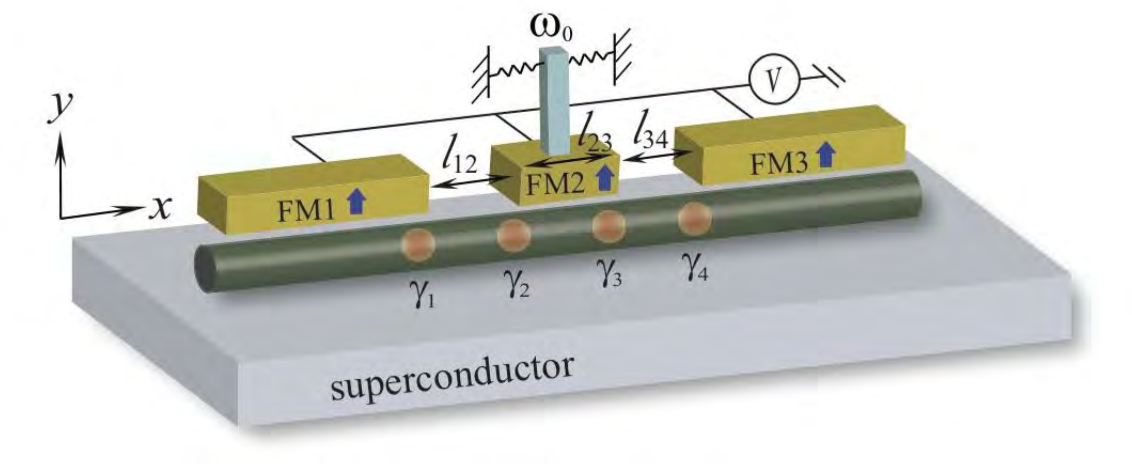

Fig. 1: Schematic diagram of the proposed Majorana qubit-nanomechanical resonator hybrid system. A semiconductor nanowire is placed on the surface of an s-wave superconductor. Three FM gates are on top of the nanowire, of which FM1 and FM3 are sufficiently long (of the order of 1-10 μm) and static, while FM2 is relatively short (of the order of 100 nm) and free to oscillate as a harmonic oscillator. The FM gates induce a local Zeeman splitting in the underlying nanowire, and can also be used to modulate the local Rashba SOC strength by applying an electric voltage.

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Measurement-based Formulation of Quantum Heat Engine and Optimal Efficiency with Finite-Size Heat Baths

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Today, theoretic analysis about quantum-scale heat engines is achieving a splendid success. They clarify that the average performance of these small-size heat engines obeys the second law of the macroscopic thermodynamics [1,2], and that the single-shot performance of the heat engines obeys different rules [3,4]. They also clarifies the thermodynamic laws for information processing [5,6]. However, in spite of these success, there are still two unsolved problems for constructing the thermodynamics of small-size systems. First, the above researches formulate the quantum heat engine in various ways, and the relationship among the formulations has not been sufficiently discussed. Second, they treat the heat baths as a kind of resource which we can use freely. However, in real, there is no free resource, in particular, when the work is extracted from two baths with different temperatures. To reflect such realistic situations, we have to take into account the finiteness of the heat baths.

In this presentation, we firstly classify the previous formulations of quantum heat engines, and derive a trade-off relation that clarifies a problem of a widely-used formulation of quantum heat engine controlled by a classical controller, in which the time evolution of the internal system (working body and heat baths) is formulated as a unitary transformation. In order to dissolve this problem, we remodel a quantum heat engine controlled by a classical controller as a general measurement process.

Second, we derive the optimal efficiency of quantum (or classical) heat engines whose heat baths are n-particle systems. We give the optimal work extraction process as an energy-preserving unitary time evolution among the heat baths and the work storage. During the unitary, the entropy gain of the work storage is so negligibly small as compared with the energy gain of the work storage, i.e., we can interpret the energy gain as the extracted work. The details of our results are in arXiv:1504.06150.v2 and arXiv:1405.6457.

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Parity-time-broken optomechanics

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We propose to study cavity optomechanic in the exotic Parity-Time-symmetry-broken regime. We find that in this regime, (i) the phonon laser is suddenly terminated due to coalesce of optical super-modes; (ii) the periodic optical oscillations are replaced by the low-power chaos, due to the shut-down of energy exchange channels between photons and phonons; (iii) the group delay of signal light is reversed from positive (slow light) to negative (advance), due to the gain-assisted optomechanically-induced transparency. Our work opens up the prospect of Parity-Time devices with photons and phonons.

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