Redefining metrics in near-term devices for quantum information processing

Antonio Córcoles *IBM*
E-mail: adcorcol@us.ibm.com

The outstanding progress in experimental quantum computing over the last couple of decades has pushed multi-qubit gate error rates in some platforms well below 1%. However, as the systems have grown in size and complexity so has the richness of the interactions within them, making the meaning of gate fidelity fade when taken isolated from its environment. In this talk I will discuss this topic and offer alternatives to benchmark the performance of small quantum processors for near-term applications.

Efficient simulation of quantum error correction under coherent error based on non-unitary free-fermionic formalism

Yasunari Suzuki[1,2], Keisuke Fujii[3,4], and Masato Koashi[1,2]
[1]*Department of Applied Physics, Graduate School of Engineering,*
The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
[2]*Photon Science Center, Graduate School of Engineering,*
The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
[3] *Department of Physics, Graduate School of Science,*
Kyoto University, Kitashirakawa Oiwake-cho, Sakyo-ku, Kyoto, 606-8502, Japan
[4]*JST, PRESTO, 4-1-8 Honcho, Kawaguchi, Saitama, 332-0012, Japan*

In order to realize fault-tolerant quantum computation, tight evaluation of error threshold under practical noise models is essential. While non-Clifford noise is ubiquitous in experiments, the error threshold under non-Clifford noise cannot be efficiently treated with known approaches. We construct an efficient scheme for estimating the error threshold of one-dimensional quantum repetition code under non-Clifford noise[1]. To this end, we employ non-unitary free-fermionic formalism for efficient simulation of the one-dimensional repetition code under coherent noise. This allows us to evaluate the effect of coherence in noise on the error threshold without any approximation. The result shows that the error threshold becomes one third when noise is fully coherent. Our scheme is also applicable to the surface code undergoing a specific coherent noise model. The dependence of the error threshold on noise coherence can be explained with a leading-order analysis with respect to coherence terms in the noise map. We expect that this analysis is also valid for the surface code since it is a two-dimensional extension of the one-dimensional repetition code. Moreover, since the obtained threshold is accurate, our results can be used as a benchmark for approximation or heuristic schemes for non-Clifford noise.

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Efficient microwave to optical photon conversion: an electro-optical realisation

Harald G. L. Schwefel

The Dodd-Walls Centre for Photonic and Quantum Technologies, Department of Physics, Univ. of Otago, Dunedin, New Zealand E-mail: Harald.Schwefel@otago.ac.nz

The emerging quantum information technology has developed similar requirements as classical information processing: while the computation is done at electronic (gigahertz) frequencies, the transfer of information utilizes optical fibers. Superconducting qubits operating at gigahertz frequencies are promising candidates for scalable quantum processors [1], while the optical domain offers access to a large set of very well developed quantum optical tools, such as highly efficient single-photon detectors and long-lived quantum memories. In addition, microwave signals carrying quantum information cannot be transferred at room temperature due to thermally induced decoherence. On the contrary, optical channels do not have this drawback. Therefore, for large scale quantum networks, it is vital to develop a noiseless and efficient conversion channel between these vastly different frequency domains.

Efficient direct electro-optic modulation has been discussed by Tsang [2] as an promising alternative to opto-mechanical approaches [3] to achieve quantum state transfer between the microwave and the optical domain. Hereby, the microwave modulates the refractive index of a nonlinear crystal resulting in phase modulation of the optical light. This typically creates sidebands symmetrically positioned around the optical pump frequency.

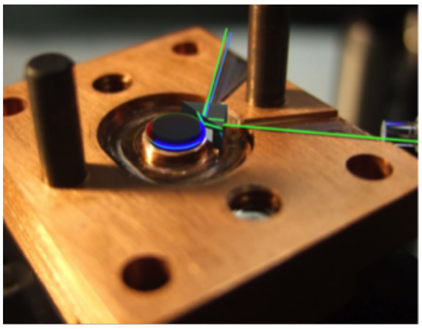

Figure 1: Three dimensional microwave cavity with rendered WGM resonator.

In our experiment we coupled a high quality optical whispering gallery mode (WGM) resonator to a microwave cavity [4] resulting in a highly efficient electro-optic modulator. By carefully designing the geometry, we managed to match the spectral distance of adjacent optical modes with the frequency of the microwave resonator. This configuration converts a microwave input field into the optical sidebands with a quantum efficiency of 0.2%. To get a noiseless and hence quantum coherent conversion, the red-detuned sideband has to be suppressed since it entails a fundamental amount of amplifier noise. We achieved this suppression by exploiting avoided crossings in the optical spectrum which modify the spectral positions of some modes allowing us to tune the system into single sideband operation. Our cavity design is compatible with cavity QED systems and can operate in cryogenic environments almost as it is. By doing so, we expect a further significant improvement of the conversion process approaching unity photon number conversion efficiency.

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Laser cooling of single-mode phononic wires and quantum electro-optics

Amir H. Safavi-Naeini, Patricio Arrangoiz-Arriola, Wentao Jiang, Tim P. McKenna, Rishi Patel, Marek Pechal, Chris Sarabalis, Zhaoyou Wang, Jeremy D. Witmer, E. Alexander Wollack, Raphael Van Laer *Department of Applied Physics, Ginzton Lab, Stanford University*
E-mail: safavi@stanford.edu

In this talk I will present the work of our lab on hybrid optomechanical and electro-optic devices operating in the quantum regime.

First, I will present our results on phononic wires. Photons and electrons transmit information to form complex systems and networks. Phonons on the other hand, the quanta of mechanical motion, are often considered only as carriers of thermal energy. Nonetheless, their flow can also be molded by fabricating nanoscale circuits. We report the demonstration of a single-mode phononic wire. Coupling the wire to a localized optomechanical transducer allows us to excite and detect phonons, and to observe their low-loss coherent transport across a chip. We strongly couple the phononic wire to the light field by detuned laser driving of the optomechanical transducer, resulting in sympathetic cooling of he wire to a temperature below that of the surrounding cryogenic environment.

In the latter part of the presentation, I will persent our preliminary work on demonstrating a fully packaged electro-optic converter functioning inside a dilution fridge to couple light and microwave frequency photons.

Quantum hybrid systems with surface acoustic waves

Atsushi Noguchi

Research Center for Advanced Science and Technology (RCAST),
The University of Tokyo, Meguro-ku, Tokyo, 153-8904, Japan,
PRESTO, Japan Science and Technology Agency, Kawaguchi-shi, Saitama 332-0012, Japan,

Hybrid quantum systems have been widely studied in quantum information science [1]. Among the several quantum systems, surface acoustic waves (SAW) have recently attracted much interest as an alternative quantum mode localized on a surface of a material [2]. In piezoelectric materials, SAW can be strongly coupled to electric fields between surface electrodes and are widely applied in compact microwave components because of their short wavelength and small losses. SAW can also couple to other physical systems [3] such as superconducting qubit, quantum dots and NV centers through various form of elastic effects. Opto-elastic interaction of SAW opens the possibility to achieve a quantum transducer from microwave photons to optical photons in the telecommunication band.

Here, we report experiments on a hybrid quantum system consisting of a SAW resonator, a superconducting qubit, and a MW resonator [4]. We demonstrate microwave-driven parametric couplings induced by the nonlinearity of the qubit, which serves as a transducer or an interface between the phonons in the SAW resonator and the photons in the MW resonator. The thermal phonons in the sub-GHz SAW resonator are up-converted to the MW frequency range where near-quantum-limited measurement of photons is available. We observe thermal fluctuations in the SAW resonator below the mean phonon number of unity with an unprecedented sensitivity. We also report a new technique to enhance the coupling strength between the SAW and MW resonators with the superconducting parametric circuits, and some technical challenges towards the quantum hybrid system including the optical systems.

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Probing many-body dynamics on a 51-atom quantum simulator

Ahmed Omran[1,*], Hannes Bernien[1], Alexander Keesling[1], Harry Levine[1], Sylvain Schwartz[1,2], Hannes Pichler[1,3], Soonwon Choi[1], Manuel Endres[4], Markus Greiner[1], Vladan Vuletić[2] & Mikhail D. Lukin[1]

[1]*Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[2]*Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[3]*ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*
[4]*Division of Physics, Mathematics and Astronomy, California Institute of Technology, Pasadena, CA 91125, USA*
[*]*E-mail: aomran@fas.harvard.edu*

The realization and control of large-scale quantum systems is an exciting frontier of modern physical science. Using a novel cold atom platform, we trap single neutral atoms in an array of optical tweezers, and use real-time feedback to prepare defect-free chains of tens of atoms in one dimension with a high fidelity and repetition rate. Excitation of the atoms to Rydberg states enables strong and tunable van der Waals interactions over long distances, which allows for engineering an Ising-type Hamiltonian with non-trivial spatial correlations between Rydberg atoms. Employing adiabatic transitions into crystalline states of Rydberg atoms, we study the properties of the system close to a phase transition. Furthermore, we study the quench dynamics of Rydberg crystals and uncover signatures of entanglement in Rydberg chains.

Atomic Spin Entanglement and Anyonic Fractional Statistics in an Optical Lattice

Zhen-Sheng Yuan

Hefei National Laboratory for Physical Sciences at Microscale and Department of Modern Physics, and CAS Centre for Excellence and Synergetic Innovation Centre in Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, China.

In this talk, I will report our recent research progress with ultracold atoms trapped in optical lattices. Ultracold atoms in optical lattices hold promise for the creation of entangled states for quantum simulation and quantum computation. In our experiment, we developed a novel setup of spin-dependent optical superlattice. We were able to generate, manipulate and detect the atomic spin entanglement in this lattice. Moreover, based on the techniques of precisely manipulating atomic spins, we built a minimum version of the toric code Hamiltonian with four atomic spins in optical plaquettes. We observed four-body ring-exchange interactions, existing in many-body systems while never observed before in experiment, and the topological properties of anyonic excitations within this ultracold atom system. This work represents an essential step towards studying topological matters with ultracold atoms and offers new perspectives on topological quantum simulation.

Zeno Hall Effect

Masahito Ueda *RIKEN CEMS, University of Tokyo*
E-mail: ueda@phys.s.u-tokyo.ac.jp

We show that the quantum Zeno effect gives rise to the Hall effect by tailoring the Hilbert space of a two-dimensional lattice system into a single Bloch band with a nontrivial Berry curvature. In particular, we find retroreflection at the edge of the system due to an interplay between the band flatness and the nontrivial Berry curvature.

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Mo09

Topological Phenomena and Relativistic Fermions in Superfluid ^{3}He

Hiroki Ikegami
RIKEN CEMS, Wako, Saitama 351-0198, Japan

The *p*-wave superfluid ^{3}He is a textbook example of topological superfluids. Owing to the nontrivial topology of the order parameter, the superfluid ^{3}He hosts emergent relativistic excitations such as Majorana and Weyl Fermions. In this talk, I discuss topological aspects of the superfluid ^{3}He and present observations of relativistic Fermions by transport of an electron (electron bubble) in the superfluid ^{3}He.

In this talk, I first demonstrate detection of Majorana surface bound states formed at a free surface of the B phase (^{3}He-B) by the mobility of an electron (Fig. 1) [1,2]. ^{3}He-B is a time-reversal invariant topological superfluid hosting Majorana Fermions at a surface as bound states. The free surface is clean and microscopically flat, and therefore it offers an ideal platform to investigate exotic properties of the Majorana surface bound states. Our observation of Majorana surface bound states at such an ideal surface is an important first step for further investigations of exotic Majorana properties.

Next, I show discovery of the anomalous Hall effect (AHE) for an electron moving in the A phase (^{3}He-A) [3] and discuss the role of Weyl Fermions for the AHE [4]. ^{3}He-A is known as a chiral *p*-wave superfluid with broken time-reversal symmetry (TRS) hasting Weyl Fermions as low-energy excitations. The Weyl Fermions exhibit skew-scattering by the electron in ^{3}He-A, which results in the AHE for the moving electron. Our finding of the AHE is also the first direct demonstration of breaking of TRS in ^{3}He-A.

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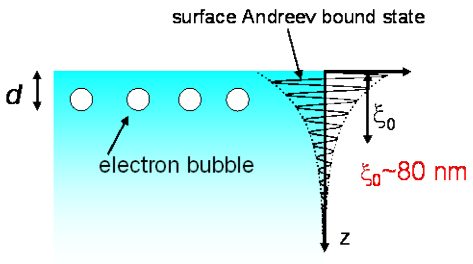

Fig.1. Majorana surface bound states and electrons trapped below a free surface of ^{3}He-B.

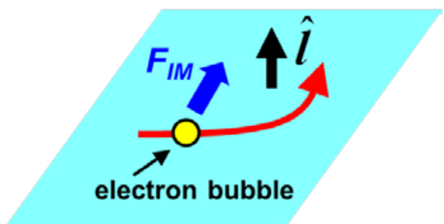

Fig.2. The anomalous Hall effect (AHE) for an electron moving in ^{3}He-A.

Quantum transport experiments with cold atoms

Jean-Philippe Brantut
EPFL, CH-1015 Lausanne, Switzerland
E-mail: jean-philippe.brantut@epfl.ch

Over the last decade, the level of control over cold atomic gases has improved to the point that atoms can now be used to simulate the behavior of electrons in realistic materials. I will present our newly developed capabilities of manipulating and observing transport at the scale of the Fermi wavelength using scanning gate microscopy techniques. I will then introduce heat transport measurements performed with strongly interacting Fermi gases, in particular new measurements of the Lorenz number and Seebeck coefficients for a finite temperature unitary Fermi gas in a quantum point contact. New perspectives for the high resolution measurement of atomic currents using quantum optics techniques will be briefly described.

Generating nonlocal quantum correlations between distant quantum-dot spins via optical measurement

Mete Atatüre

University of Cambridge, JJ Thomson Ave., Cambridge CB3 0HE, UK

Optically active spins confined in solids, such as semiconductor quantum dots, offer realistic opportunities for realizing stationary and flying qubits within the context of spin-based quantum information science, particularly for distributed quantum network architectures. Their inherently mesoscopic nature leads to a multitude of dynamics within the solid-state environment of spins, charges, vibrations and light. While the quantum optics has provided the toolbox for advanced spectroscopic investigations for these interaction mechanisms, it has also offer solution possibilities for their detrimental effects. Implementing a high level of control on these constituents and their interactions with each other creates tailored spin-photon quantum interfaces with optimal properties. In this talk, I will provide a snapshot of the progress and challenges for quantum optically interconnected solid-state spins, with focus on generating high-bandwidth nonlocal quantum correlations in self-assembled quantum dots via coherently scattered single photons. I will also discuss current steps towards improving both the spin coherence and the entanglement generation rate in the future.

Single-Photon Quantum Technology with Quantum Dots

P. Lodahl
Center for Hybrid Quantum Networks (Hy-Q), Niels Bohr Institute, University of Copenhagen, Denmark
lodahl@nbi.ku.dk

Semiconductor quantum dots have improved their optical performance dramatically in recent years, and today a clear pathway is laid out for constructing a deterministic and coherent photon-emitter interface by embedding quantum dots in photonic nanostructures [1]. Such an interface can be employed as an on-demand single-photon source for quantum-information applications, but more generally enables single-photon nonlinearities and deterministic quantum gates [2]. We will review the recent experimental progress on quantum dots coupled to nanophotonic waveguides and cavities enabling unique ways of engineering light-matter interaction. A single-photon coupling efficiency exceeding 98.4% is reported [3] and the indistinguishability of the emitted photons is extracted [4] and the fundamental limits exploited [5]. Furthermore, various out-coupling strategies for efficiently transferring single photons to an optical fiber are implemented [6]. Finally, the unique engineering potential of the nanophotonic waveguides is demonstrated by implementing a chiral quantum interface [7,8]. The prospects and applications of single-photon nonlinearities [9,10] and architectures for scalable quantum networks are discussed [11].

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Deterministic Generation of Remote Entanglement with Microwave Photons

Andreas Wallraff
Department of Physics, ETH Zurich, CH-8093 Zurich, Switzerland
URL: https://www.qudev.ethz.ch

Sharing information coherently between nodes of a quantum network is at the core of quantum communication and distributed quantum information processing. Here, we discuss our progress toward implementing a deterministic quantum state transfer and remote entanglement protocol with microwave photons in a circuit QED architecture. We embed a superconducting transmon-type three level system in a transmission line resonator at two spatially separated nodes. We generate an itinerant shaped microwave photon based on a microwave drive induced second-order process [1] and transmit it via a coaxial line [2]. Emitting and absorbing the single photon with high fidelity ideally achieves coherent qubit state transfer or remote entanglement generation. Our approach, therefore, may open a viable path toward all-microwave quantum networks based on deterministic interactions between distant nodes.

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Inversion of qubit energy levels in deep-strongly-coupled qubit-oscillator circuits

F. Yoshihara[1], T. Fuse[1], Z. Ao[2], S. Ashhab[3], K. Kakuyanagi[4], S. Saito[4], T. Aoki[2], K. Koshino[5], and K. Semba[1]

[1]*Advanced ICT Institute, National Institute of Information and Communications Technology,* [2]*Department of Applied Physics, Waseda University,* [3]*Qatar Environemnt and Energy Research Institute, Hamad Bin Khalifa University, Qatar Foundation,* [4]*NTT Basic Research Laboratories, NTT Corporation,* [5]*College of Liberal Arts and Sciences, Tokyo Medical and Dental University*

The electromagnetic field inside a cavity renormalizes the transition frequency of an atom inside the cavity. The Lamb (n = 0) and n-photon ac-Stark shifts can be written as $\Delta - \Delta_n$, where Δ and Δ_n are respectively the transition frequencies of a non-interacting and renormalized atom. In the limit of $\Delta \ll \omega$, where ω is the resonance frequency of the cavity, Δ_n can be written as[1]

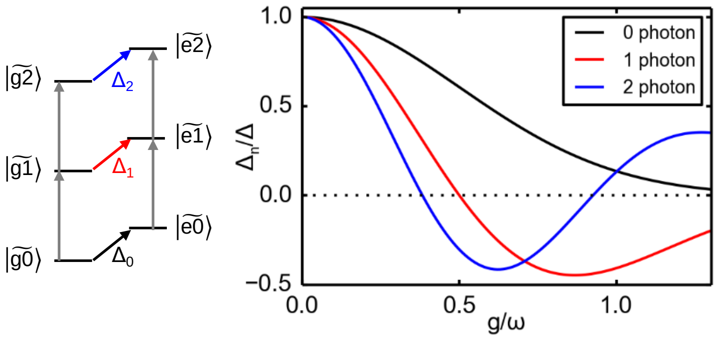

Fig. 1 (left) The diagram of six lowest energy-levels of a qubit-oscillator circuit. The energy eigenstates $|\widetilde{in}\rangle$ (i = g, e) indicates that the qubit is in "g" the ground or "e" the excited states and the oscillator is in the n-photon Fock state. The arrows indicate allowed transitions. (right) Calculated Δ_n given by Eq. (1) as functions of g/ω.

$$\Delta_n/\Delta = \exp[-2(g/\omega)^2]L_n[(2g/\omega)^2] \quad (1),$$

where g is the coupling constant between the atom and the electromagnetic field inside the cavity and L_n is a Laguerre polynomial. Δ_n (Fig. 1 right) has n zeros, reflecting the nature of Laguerre polynomials. This expression indicates considerable Lamb shifts as g becomes comparable to ω. It also indicate that the n-photon ac-Stark shifts are so large that the atom's transition frequency changes sign when L_n crosses zero; the atom's ground and excited states are "inverted".

We use circuits of a superconducting flux qubit deep strongly coupled to an LC oscillator[2], where $g \sim \omega$ and $g > \Delta$. The experimentally observed qubit frequencies Δ_n (n = 0, 1, 2) for g/Δ ranging from 0.86 to 1.18 were very close to those given by Eq. (1).

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Exploiting two-photon driving in circuit QED: synthetic strong coupling and entangled cat states

Aashish Clerk

Institute for Molecular Engineering, University of Chicago, Chicago, USA

The ability to parametrically drive a photonic cavity is a powerful resource with applications far beyond parametric amplification. I will discuss recent theory work in my group exploring two such directions. The first part will focus on how parametric driving allows a weak-coupling cQED system to exhibit strong coupling behaviour and even physics associated with the ultra-strong coupling regime. The drive-enhanced coupling can be time-dependent, enabling a number of new functionalities. The second part will focus on how parametric driving combined with Kerr interactions can be used to dissipatively prepare and stabilize entangled cat states in two distant cavities.

Scaling up single-atom spin qubits in silicon

Andrea Morello
School of Electrical Engineering & Telecommunications
Centre for Quantum Computation & Communication Technology
UNSW Sydney, Australia

The modern information era is built on silicon nanoelectronic devices. The future quantum information era might be built on silicon too, if we succeed in controlling the interactions between individual spins hosted in silicon nanostructures.

Spins in silicon constitute excellent solid-state qubits, because of the weak spin-orbit coupling and the possibility to remove nuclear spins from the environment through 28Si isotopic enrichment. Substitutional 31P atoms in silicon behave approximately like hydrogen in vacuum, providing two spin 1/2 qubits -- the donor-bound electron and the 31P nucleus -- that can be coherently controlled [1,2], read out in single-shot [2,3], and are naturally coupled through the hyperfine interaction.

In isotopically-enriched 28Si, these single-atom qubits have demonstrated outstanding coherence times, up to 35 seconds for the nuclear spin [4], and 1-qubit gate fidelities well above 99.9% for both the electron and the nucleus [5]. The hyperfine coupling provides a built-in interaction to entangle the two qubits within one atom. The combined initialization, control and readout fidelities result in a violation of Bell's inequality with S = 2.70, a record value for solid-state qubits [6].

Despite being identical atomic systems, 31P atoms can be addressed individually by locally modifying the hyperfine interaction through electrostatic gating [7]. Multi-qubit logic gates can be mediated either by the exchange interaction [8] or by electric dipole coupling [9].

Scaling up beyond a single atom presents formidable challenges, but provides a pathway to building quantum processors that are compatible with standard semiconductor fabrication, and retain a nanometric footprint, important for truly large-scale quantum computers.

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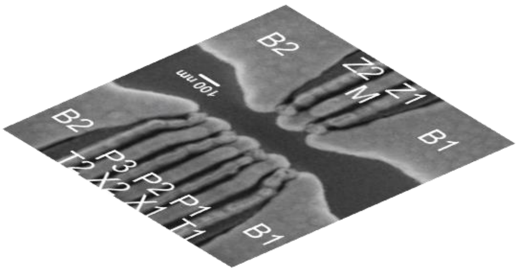
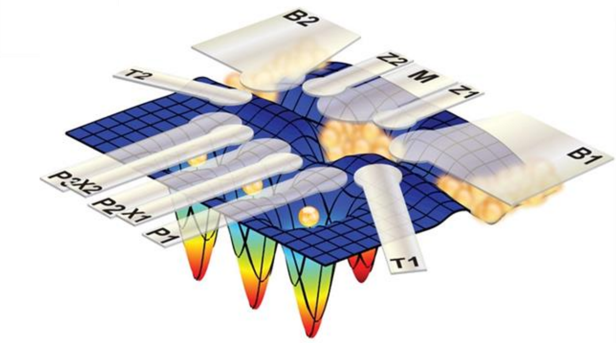
Tu07

Isotopically Enhanced Triple-Dot Qubits in SiGe

Thaddeus D. Ladd
HRL Laboratories, LLC

Qubits based on silicon offer the promise of low magnetic noise due to isotopic enhancement and the availability of existing silicon growth and fabrication processes. Triple-dot qubits offer promise of exchange-only spin-qubit control, enabling operation using only gate voltages. The main impediments to silicon qubits are interface disorder, charge noise, valley degeneracy, and nuclear magnetism. In this talk, I will summarize recent data characterizing these impediments for SiGe triple dots fabricated in an undoped accumulation-mode gate architecture, including symmetric barrier control to mitigate charge noise [1], and isotopic enhancement to mitigate nuclear noise [2]. I will then discuss the mathematics of pulse sequences allowing gauge-independent quantum logic, enabling future developments for exchange-only multiqubit quantum processors.





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Rapid single and two-qubit manipulations of electron spins in a GaAs triple quantum dot

Takashi Nakajima

Center for Emergent Matter Science (CEMS), RIKEN, Wako-shi, Saitama, Japan

Gate-defined quantum dots are a promising platform for solid-state quantum computation. This is partly evidenced by high-fidelity control of electron-spin qubits[1,2], but there remain practical challenges to realize a quantum computation architecture.

One of such challenges is the drift of qubit frequency caused by magnetic/electrostatic fluctuation in the host material. This leads to the inhomogeneous dephasing effect and errors in qubit control. Here, we demonstrate that the effect of the frequency drift can be mitigated by operating a GaAs single-electron spin qubit in a frequency-locked loop. By monitoring the instantaneous qubit frequency subject to the Overhauser field fluctuation via rapid Ramsey measurement, the microwave frequency for qubit drive is locked into the desired qubit frequency[3]. We observed that long-term drift of the qubit frequency is perfectly compensated and found almost 30-fold improvement of the inhomogeneous dephasing time.

Another challenge in spin-based quantum computation is that readout and initialization of spin qubits are orders of magnitude slower than qubit control. To overcome this challenge, we realized a hybrid system of a single-spin qubit and a singlet-triplet (ST) qubit in a GaAs triple quantum dot, where the latter allows much faster readout and initialization of the qubit state. The exchange interaction *J* between the two different kinds of qubits shifts the frequency of the target qubit depending on the state of the control qubit[4]. We demonstrate a controlled-phase gate operation as fast as 5 ns by rapidly switching *J*. This hybrid architecture may open a new route toward efficient spin-based quantum computation.

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Scaling up a superconducting qubit lattice with parametric gates

Blake Johnson (speaker), Shane Caldwell, Colm Ryan, Riccardo Manenti, Michael Scheer, Max Block, Schuyler Fried, Diego Scarabelli, Alex Hudson, Marcus P. da Silva, Chad Rigetti

Rigetti Computing, Berkeley, CA

Scaling up superconducting qubit systems presents a number of challenges in various domains including: control systems, fabrication, packaging, signal delivery, and software automation. I will report on initial efforts toward scaling up Rigetti's 8-qubit platform toward larger lattices of qubits and how we address some of these challenges. In particular, I will examine the performance and operating point discovery of parametric gates in lattices with larger connectivity. This will touch on operational measures of crosstalk, such as dependence of simultaneous benchmarking on distance (in real space and frequency space) between qubit subsystems.

Tu10

Spectral signatures of many-body localization of interacting photons

P. Roushan[1], C. Neill[2], J. Tangpanitanon[3], V.M. Bastidas[3], A. Megrant[1], R. Barends[1], Y. Chen[1], Z. Chen[2], B. Chiaro[2],A. Dunsworth[2], A. Fowler[1], B. Foxen[2], E. Jeffrey[1], J. Kelly[1], E. Lucero[1], J. Mutus[1], M. Neeley1’ C. Quintana[2], D. Sank[1], A. Vainsencher[2], J. Wenner[2], T. White[1], H. Neven[1], D. G. Angelakis[3;4], J. Martinis[1;2]

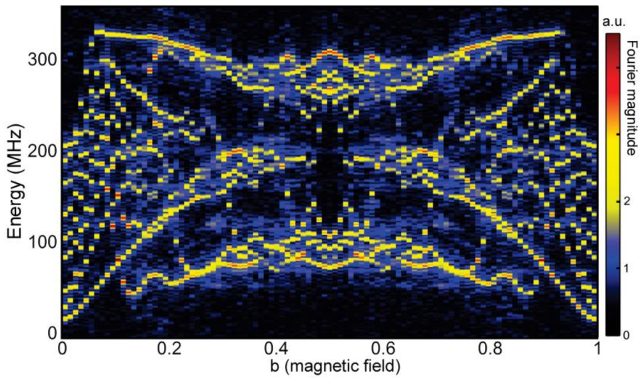
[1]*Google Inc., Santa Barbara, California, USA*

[2]*Department of Physics, University of California, Santa Barbara, California, USA*

[3]*Centre for Quantum Technologies, National University of Singapore, Singapore*

[4]*School of Electrical and Computer Engineering, Technical University of Crete, Crete, Greece*

Statistical mechanics is founded on the assumption that a system can reach thermal equilibrium, regardless of the starting state. Interactions between particles facilitate thermalization, but, can interacting systems always equilibrate regardless of parameter values ? The energy spectrum of a system can answer this question and reveal the nature of the underlying phases. However, most experimental techniques only indirectly probe the many-body energy spectrum. Using a chain of nine superconducting qubits, we implement a novel technique for directly resolving the energy levels of interacting photons. We benchmark this method by capturing the intricate energy spectrum predicted for 2D electrons in a magnetic field, the Hofstadter buttery. Increasing disorder leads to the formation of a mobility edge, where the spatial extent of energy eigenstates shrink at the edge of the energy band. At strong disorder, the energy levels cease to repel one another and their statistics approaches a Poisson distribution - the hallmark of transition from metallic to the many-body localized phase. Our work introduces a new many-body spectroscopy technique to study quantum phases of matter.



Using 9 superconducting qubits, we simulate the problem of Bloch electrons on a 2D lattice subject to a perpendicularly applied magnetic field. We directly measure the energy spectrum of the system, which was first calculated by Hofstadter and resembles a butterfly.

Non-equilibrium dynamics in a quantum-Hall Tomonaga-Luttinger liquid

Toshimasa Fujisawa
Department of Physics, Tokyo Institute of Technology, Japan.

Interacting electrons in one-dimensional (1D) conductors can be described by non-interacting plasmons in the Tomonaga-Luttinger (TL) model [1]. For spin-full 1D channels, spin and charge density excitations travel independently as collective modes, known as spin-charge separation. Intriguingly, the TL model suggests that the system does not experience thermalization as long as coupling to external degree of freedom can be neglected [2]. This means that 1D channels can be considered as a transmission medium for free plasmons rather than electrons. TL liquids in quantum Hall (QH) edge channels are attractive for studying non-equilibrium plasmon transport as various functional devices can be attached to the channels for investigating non-equilibrium states.

In this talk, I would like to introduce some recent experiments that characterize the Tomonaga-Luttinger behaviours in the QH edge channels. For example, an electrical pump-and-probe scheme is employed to measure waveforms of plasmon wave packets, from which the spin and charge modes of the TL liquid are clearly identified [3,4]. Quantum-dot spectroscopy allows us to investigate the energy distribution function, from which two-stage equilibration via a long-lived metastable state is investigated [5,6]. These experiments elucidate plasmon transport in quantum Hall edge channels.

I would like to thank collaborators; M. Hashisaka, N. Hiyama, H. Kamata, N. Kumada, K. Muraki, R. Nakazawa, T. Ota, Y. Tokura, and K. Washio. This work is supported by JSPS KAKENHI (26247051 and 15H05854) and TokyoTech Nanotechnology Platform.

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NMR implementation of quantum reservoir computing

Makoto Negoro
Graduate School of Engineering Science, Osaka University
JST PRESTO

Reservoir computing is a framework for computation using a neural network (called *reservoir* in this context), where the internode transition is not trained but instead linear readout weight is trained [1]. Recently a quantum counterpart of reservoir computing was proposed [2]. Here, we implement quantum reservoir computing with ensemble nuclear spin qubits as network nodes. Our qubit system is comprised of nuclear spins in a small molecule diluted into a single crystal of isotopically labelled one. The qubit state is transited with the dipole-dipole interactions. Data input is represented by phase of NMR pulse sequence. The ^{13}C spin state is read out by NMR signal. In this talk, we show the results and discuss the scalability of the architecture.

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Progress towards a Trapped Ion Quantum Computer

Jungsang Kim*, Stephen Crain, Geert Vrijsen, Volkan Inlek, James Joseph, Chao Fang, Robert Spivey, George Schwartz, Yuhi Aikyo

Department of Electrical and Computer Engineering and Department of Physics

Duke University, Durham, NC 27708, USA

**Also with IonQ, Inc., College Park, MD 20740, USA*

Quantum computers are expected to solve some important computational problems that are believed to be intractable using conventional classical computers. Recent progress in the development of high quality quantum bits and their successful manipulation in various physical systems have led to significant confidence that a moderate scale quantum computers can be constructed, in leading physical platforms such as trapped ions and superconducting circuits. In this talk, I will discuss the current status of research effort towards constructing a scalable quantum processor using trapped ions, leveraging state-of-the-art technical progress leveraging micro-fabricated ion traps, optical micro-electromechanical systems, advanced optical modulators and laser systems.

Optical hybrid quantum teleportation and its application to large-scale quantum computing

Shuntaro Takeda[1,2,*] and Akira Furusawa[1]
[1]*Department of Applied Physics, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*
[2]*JST, PRESTO, 4-1-8 Honcho, Kawaguchi, Saitama, 332-0012, Japan*
[*]*E-mail: takeda@ap.t.u-tokyo.ac.jp*

Quantum teleportation is a way of transferring an unknown quantum state from one quantum system to another. Optical quantum teleportation has been experimentally realized both in qubit and continuous-variable (CV) systems, but both approaches have pros and cons. Here we take a "hybrid" approach combining photonic qubits and a CV teleportation device. This approach can take advantage of both robust encoding of qubits and deterministic operation of CVs, enabling us to demonstrate efficient transfer of photonic qubits [1], single-photon entanglement [2], as well as two-photon qutrits [3].

One of the promising applications of the hybrid teleportation is quantum computation; deterministic quantum logic gates based on CV teleportation can be used to efficiently process not only CVs but also qubits. We propose a scalable quantum computation scheme where such teleportation-based gates are sequentially performed in a loop-based architecture (Fig.1) [4]. This architecture can programmably perform large-scale quantum computing with almost minimum resources, and offers a universal gate set for both qubits and CVs. All the elements of this architecture are within reach of our hybrid technologies.

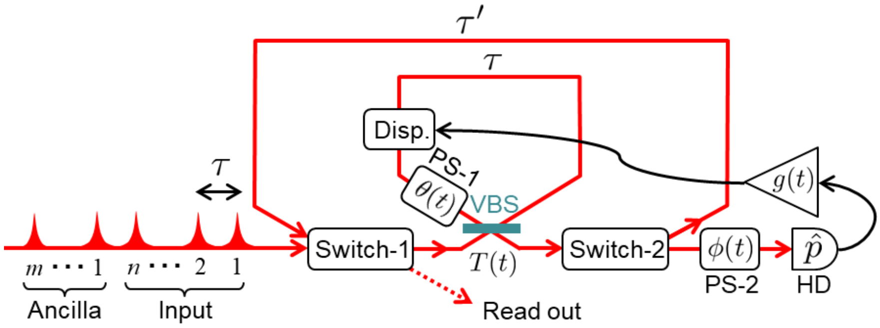

Figure 1: Loop-based architecture for universal quantum computing. HD, Homodyne Detector; Disp., Displacement operation; PS, Phase shifter; VBS, Variable beam splitter.

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Quantum nonlinear optics
with distinguishable and indistinguishable photons

Gerhard Rempe

Max Planck Institute of Quantum Optics, Hans-Kopfermann-Str. 1, 85748 Garching, Germany

Photons do not interact in vacuum as they carry neither mass nor charge. However, controlled interactions can be mediated by optically nonlinear media. A paradigm is a single atom trapped at the center of a high-finesse optical cavity. In this system, indistinguishable photons of a light field experience strong interactions when resonantly driving an atomic transition that couples strongly to a single cavity mode. The underlying physics comes from the anharmonic energy level structure of the strongly coupled system that can be employed for the realization of single- and two-photon blockade effects [1]. Strong interactions can also be employed for distinguishable photons of two different light fields that drive separate cavity modes each strongly coupled to a different transition of the atom. An additional control laser can induce a tunable coupling between these modes. Here, the energy level structure is anharmonic in both photon numbers. The coupling leads to either mutual blocking or conjunct tunneling of distinguishable photons in a regime where indistinguishable photons in the same mode do not interact [2]. The effect might be used to efficiently sense, e.g., microwave photons with optical photons.

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Singlet Triplet Spin Qubits in the Rotating Frame

Amir Yacoby
Harvard University, Cambridge, MA, USA

Electron spins in semiconductors holds promise for encoding and manipulating quantum information. The weak coupling of the spin degree of freedom to its environment provides spin qubits exceedingly long storage times. However, while storage is in the spin degrees of freedom, controlling spin qubits often involves manipulating the charge degree of freedom of the participating electrons which is far more susceptible to decoherence due to charge noise. In this talk I will discuss the advantages of operating a two electron singlet-triplet qubit in the rotating frame as a way to mitigate some of the unwanted effects of charge noise. We will demonstrate a new readout scheme for these qubits which is needed for operating in the rotating frame as well as full single and two qubit process tomography demonstrating two qubit gate fidelity in excess of 0.9.

Synthetic spin orbit interaction for Majorana devices

Takis Kontos

Laboratoire Pierre Aigrain, CNRS, Ecole Normale Supérieure, Paris

In this talk, I will show how we combine superconducting contacts with a magnetic texture proximal to a carbon nanotube. We demonstrate a large synthetic spin orbit interaction which deeply modifies the induced superconducting correlations in the carbon nanotube. We also observe a zero bias conductance peak which is the hallmark of Majorana zero modes. Our findings could be used for advanced experiments, including microwave spectroscopy and braiding operations.

The Experimental status of Majorana Zero Modes in Semiconductor-Superconductor Hybrids

Charles Marcus
Center for Quantum Devices and Station Q
Niels Bohr Institute, University of Copenhagen, Denmark

This talk be an up-to-date status report on Majorana zero modes in nanowires, what open questions remai (particularly concerning distinguishing Majorana modes from Andreev bound states), how they are being addressed experimentally, and perhaps more importantly, where the field is going next. Two emerging directions are (1) extensions beyond single wires to networks that allow complex geometries and phase control, and (2) coherent control, moving toward topological qubits. In the first category, the invention of epitaxial superconductor-semiconductor two-dimensional heterostructures has opened the door to top-down processing. In the second category, experimental extensions of conventional superconducting qubits are underway. Research supported by Danish National Research Foundation and Microsoft.

Diamond quantum networks for distributed quantum computation

Tim Hugo Taminiau

QuTech & Kavli Institute of Nanoscience, Delft University of Technology

Quantum networks provide a promising way to realize large-scale quantum computations and simulations. Such networks consist of nodes that contain multiple qubits to store and process quantum states, and that are connected together by distributing entangled states through optical links using photons. Crucially, imperfections and errors can be overcome by distributing logical qubits, computations and error correction over the network [1]. This approach is scalable to large sizes by connecting many independent modules, thus avoiding the challenges of a single large structure of ever increasing complexity.

The nitrogen vacancy (NV) center in diamond is a promising candidate to realize such quantum networks, as it combines optical entanglement links [2] with long-lived multi-qubit nodes that can store and process quantum information [3-5]. In this talk I will discuss the recent progress of my group towards quantum networks for distributed quantum computations.

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Holonomic quantum manipulation of diamond qubits

Hideo Kosaka

Yokohama National University, 79-5 Tokiwadai, Yokohama 240-8501, Japan

Realization of fast fault-tolerant quantum gates on a single spin is the core requirement for solid-state quantum-information processing. As a polarized light shows geometric interference, a spin coherence is geometrically controlled with light via the spin-orbit interaction or directly with microwave. We show that a geometric spin in a degenerate subspace of a spin-1 electronic system in the nitrogen vacancy center in diamond allows implementation of optical non-adiabatic holonomic quantum gates. The geometric spin under quasi-resonant light exposure undergoes a cyclic evolution in the spin-orbit space, and acquires a geometric phase or holonomy that results in rotations about an arbitrary axis by any angle defined by the light polarization and detuning, enabling universal holonomic quantum gates with a single operation. We demonstrate the complete Pauli quantum gates using the geometric spin preparation and readout techniques for the quantum process tomography [1]. On the other hand, in the case of polarized microwave, the geometric spin undergoes a cyclic evolution in the partial space of the spin triplet states via the magnetic field component of the microwave to acquire the geometric phase, which becomes the relative phase in the degenerate logical qubit. We demonstrate the universal quantum holonomic gates using the electron and nitrogen nuclear spins in an NV center via the hyperfine interaction. The optical holonomic quantum gates open the way towards holonomic quantum computers and repeaters.

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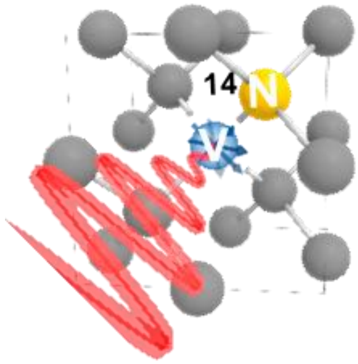

P-01

Hybrid Quantum Systems of Atoms and Superconductors

Alessandro Landra[a], Lim Chin Chean[a], Christoph Hufnagel[a], Deshui Yu[a], Rainer Dumke[a, b]

[a]*Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543, Singapore*
[b]*Division of Physics and Applied Physics, Nanyang Technological University, 21 Nanyang Link, Singapore 637371, Singapore*

Hybrid Quantum Systems combine two or more quantum systems in order to use their complementary capabilities. In particular, hybridization of atomic and solid state systems could offer a feasible way to reliably process, store and transmit quantum states in one device [R. Dumke et al J. Opt. 18, 093001 (2016)]. In our experiment we work towards the coupling between ultracold atoms and superconducting circuits.
Rb87 atoms are firstly trapped in a Magneto Optical Trap and subsequently transported, with a magnetic conveyor belt, into a dilution refrigerator with optical access. We plan to move the cloud inside a microwave cavity using a wire guide in an Ioffe configuration. Here the atoms can be excited to Rydberg state where we can take advantage of the large electric dipole moment and measure the coupling between the cavity and the cloud. Moreover the cavity can host a superconducting qubit. The presence of the Rydberg atoms changes the dielectric media and can shift resonance of the transmon qubit. This coupling will allow us to perform combined gates between atoms and superconducting circuits [D. Yu et al Phys. Rev. A 93, 042329 (2016)].

Optical Manipulation of vortex traps and hybrid atom chip

Francesca Tosto[1], Phyo Baw Swe[2], Tin Nghia Nguyen[2], Rainer Dumke[1,2]

[1]*Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543, Singapore*

[2]*Division of Physics and Applied Physics, Nanyang Technological University, 21 Nanyang Link, Singapore 637371, Singapore*

We investigate the dynamics of superconductors with ultra-cold 87Rb atoms to study the magnetic properties of superconductors and the interaction between atoms and vortices. Superconducting atom chips allow a new generation of fundamental experiments and applications, such as novel trapping geometries with the induced persistent currents and the realization of hybrid quantum systems (superconducting LC circuits or SQUIDs interacting with atoms). Combining electric, magnetic and optical fields, atoms can be trapped close to the chip surface following different schemes and patterns. We propose a versatile method for trapping ultra-cold atoms in the vortices of a high-temperature superconductor (HTS) atom chip by using a high-power laser and a DMD (digital micromirrors device). We can generate different trapping potential (ring, square, lattices) by programming our DMD with the chosen pattern, sending the laser light on it and transferring that pattern on the chip. We then exploit the heating effect of the laser light hitting the chip surface and the critical temperature of the superconductor to destroy and manipulate the vortices. This can be done in two different ways: we first load the vortices everywhere and we change the trap at the end by turning on the laser light or we send the laser light first and we let the vortices create only in the allowed regions. This leads to different trapping geometries and a different vortices distribution in the superconductor, paving the way to tunable traps for ultra-cold atoms, on-chip interferometers and new hybrid quantum devices.

P-03

Phase transition and mode softening in superconducting circuit

Motoaki Bamba[1,2], Kunihiro Inomata[2,3,4], and Yasunobu Nakamura[3,5]
[1] *Department of Materials Engineering Science, Osaka University, Japan*
[2] *PRESTO, Japan Science and Technology Agency (JST), Japan*
[3] *RIKEN Center for Emergent Matter Science (CEMS), Japan*
[4] *National Institute of Advanced Industrial Science and Technology(AIST), Japan*
[5] *Research Center for Advanced Science and Technology (RCAST), The University of Tokyo, Japan*
E-mail: bamba@qi.mp.es.osaka-u.ac.jp

It has been discussed for more than 40 years [1] that a transverse electromagnetic field gets a static coherent amplitude spontaneously in the thermal equilibrium when a strength of light-matter interaction is beyond a critical value. It is historically called a super-radiant phase transitions (SRPT). However, such a SRPT is not yet observed in the thermal equilibrium, while a non-equilibrium analogue in the sense of quantum phase transitions was demonstrated experimentally in 2010 [2]. In fact, it was claimed around 1980 that the thermal SRPT is in principle absent in the real atoms [3], while it is still controversial.

In contrast, we found a superconducting circuit that shows a SRPT in the sense of both thermal and quantum phase transitions [4]. The circuit and phase diagrams are shown in Fig. 1(a) and (b), respectively. A typical signature of the SRPT is the softening of excitation mode at the critical point [5]. In our system, as shown in Fig. 1(c), the lowest transition frequency (bold dashed curve) shows a cusp at the critical point in the limit of infinite number of Josephson junctions ($N \to \infty$). Increasing the number of junctions from $N = 1$ to 5, the transition frequencies for exciting odd and even number of bosons (dash-dotted and solid curves, respectively) show an asymptotic behavior approaching the infinite limit, where the parity symmetry is broken after the SRPT. Such a symmetry breaking is obtained in adiabatic process and observed in coherent dynamics in our system.

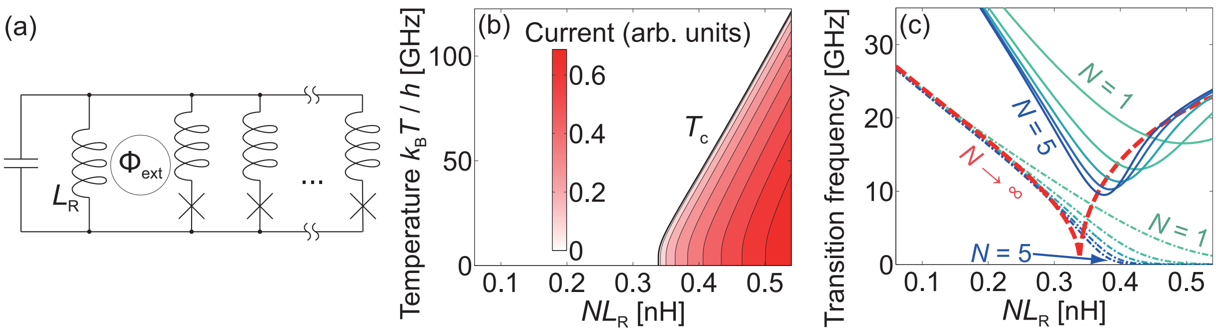

Figure 1: (a) Circuit diagram. It consists of an LC resonator connected with N Josephson junctions through inductances. An external magnetic flux Φ_{ext} is applied in a loop. (b) Phase diagram of superconducting current in the circuit. (c) Transition frequency shows a cusp (mode softening) at the critical point in $N \to \infty$ limit. See details in the text and Ref. [4].

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Coupling a single ion to an optical fiber cavity

Hiroki Takahashi, Ezra Kassa, Costas Christoforou and Matthias Keller

University of Sussex, Brighton, United Kindom

Cavity QED with single trapped ions has been pursued for long time as a promising avenue for quantum network but has not yet achieved strong coupling with a single ion. This is due to the technical difficulty in combining ion traps and dielectric cavity mirrors in a small volume. The development of fibre-based Fabry-Perot cavities has offered a new perspective for integrating small optical cavities in ion traps. Their reduced size and possibility of tight integration/electrical shielding have the potential to achieve a small cavity mode volume without seriously compromising the trapping stability.

Recently we succeeded in coupling a single trapped ion to an optical fibre cavity. We observed a Purcell effect caused by the cavity which strongly alters the photon emission property of a Calcium 40 ion (Takahashi et al. PRA 96, 023824 (2017)). Through analysis of the measurement results, we have obtained an ion-cavity coupling of 5.3 ± 0.1 MHz, the largest reported so far for a single ion in the infrared domain. The coupling is mainly limited by the spatial overlap between the ion and cavity field. However this can be further optimised by manipulating the rf field in the trap. We report on the most recent development in the experiment towards achieving strong coupling of a single ion.

P-05

All Optical Programmable Logic Array (PLA)

Dawit Hiluf Hailu[1]

[1]Department of Physical Chemistry, Ben-Gurion University of Negev, Beer-Sheva 84105, Israel

October 15, 2017

Abstract

A programmable logic array (PLA) is an integrated circuit (IC) logic device that can be reconfigured to implement various kinds of combinational logic circuits. The device has a number of AND and OR gates which are linked together to give output or further combined with more gates or logic circuits. This work presents the realization of PLAs via the physics of a three level system interacting with light. A programmable logic array is designed such that a number of different logical functions can be combined as a sum-of-product or product-of-sum form. We present an all optical PLAs with the aid of laser light and observables of quantum systems, where encoded information can be considered as memory chip. The dynamics of the physical system is investigated using Lie algebra approach. [1]

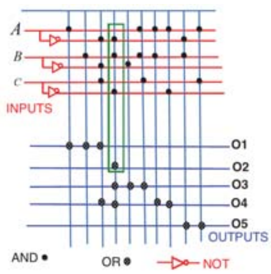


Figure 1: Programmable logic array (PLA). In digital logic language programming refers to fusing connections

[1]dawit@post.bgu.ac.il

P-06

Superconducting-Qubit Clocks

Deshui Yu[1] and Rainer Dumke[1,2]

[1]*Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543, Singapore*

[2]*Division of Physics and Applied Physics, Nanyang Technological University, 21 Nanyang Link, Singapore 637371, Singapore*

We explore the application of clock technology in superconducting circuits to enhance the coherence times of superconducting qubits. As an example, we theoretically studied the performance of a superconducting flux-qubit clock, where the periodic persistent-current oscillation is locked to the microwave ground-state hyperfine transition of ^{87}Rb atom via the clock technology (Figure 1). Our simulation illustrates that the feedback control strongly suppresses the low-frequency fluctuations of external flux, resulting in a stabilized flux-qubit Rabi oscillation. The efficiency of the proposed clock scheme is restricted mainly by the relatively long cycle time and the Dick-effect-induced down-conversion of frequency fluctuations in flux-qubit oscillation. Reducing intrinsic noises in superconducting devices is still the key issue, and it could be achieved in the near future with the development of low-temperature electronics. Our study shows that the clock technology may potentially be widely applied in solid-state quantum information processing, allowing it to be immune to environment noises.

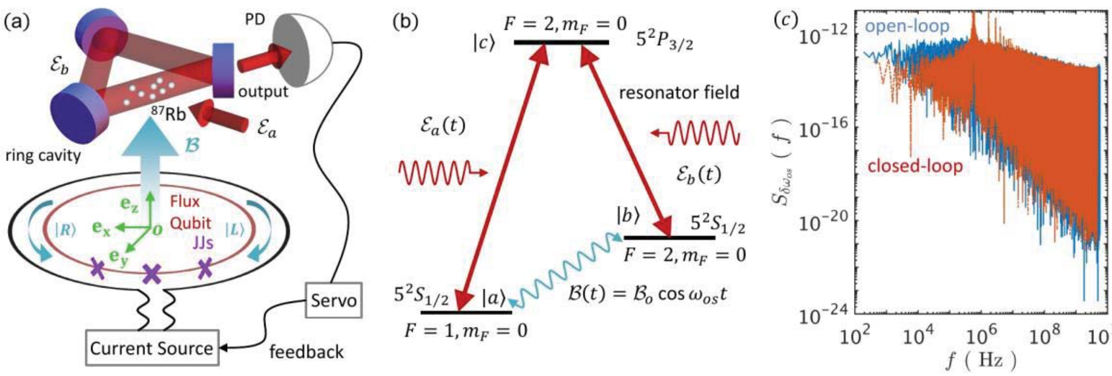


Figure 1. (a) Schematic diagram of flux-qubit clock. (b) Atomic structure. (c) Power spectral density of Rabi frequency of flux qubit.

Simulation of XY models using Josephson junction arrays in circuit QED architecture

R. Cosmic[1,2], H. Ikegami[2], Z.R. Lin[2], K. Inomata[2,3], J.M. Taylor[1,4,5], and Y. Nakamura[1,2]

[1] *Research Center for Advanced Science and Technology (RCAST), The University of Tokyo, Tokyo, Japan*
[2] *RIKEN Center for Emergent Matter Science (CEMS), Wakoshi, Japan*
[3] *National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan*
[4] *Joint Center for Quantum Information and Computer Science (QuICS), University of Maryland, College Park, MD, United States*
[5] *Joint Quantum Institute (JQI), National Institute of Standards and Technology (NIST), MD,United States*
E-mail: cosmic@qc.rcast.u-tokyo.ac.jp

Understanding and engineering of quantum many-body systems is a big challenge in quantum physics and quantum information processing. Studies in artificial quantum many-body systems with well-controlled parameters should play a central role for that purpose. Superconducting Josephson junction arrays (JJAs) are prototypical model systems consisting of an array of superconducting islands connected by small Josephson junctions. JJAs can be designed for various types of 2D lattices and have the ability to control the chemical potential and associated energy scales for studying many-body phenomena in both classical and quantum regimes. Here we present microwave studies of JJAs using a circuit QED approach (Fig.1) and report the observation of vortex lattice ordering at commensurate flux bias conditions and direct detection of plasma-mode (spin wave) spectra in a 31×3 quasi-1D JJA. We also present some recent results on many-body effects in a 100×100 square-lattice JJA.

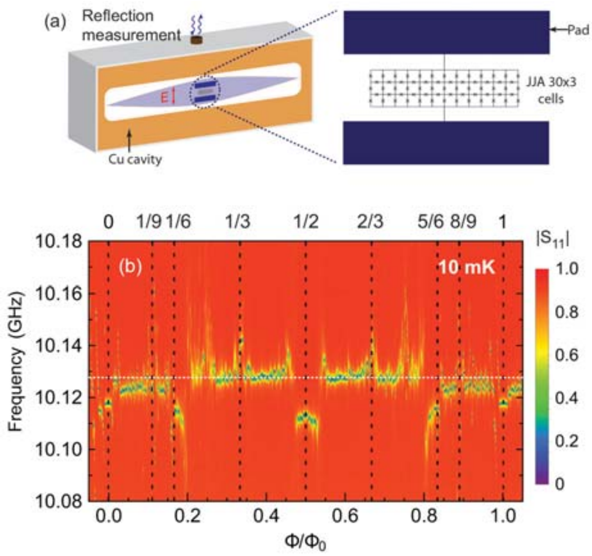


Figure 1: (a) Schematic of a Josephson junction array in circuit QED architecture. (b) $|S_{11}|$ as a function of the flux bias and the probe frequency for the JJA of $E_J/E_C = 2.0$ taken at 10 mK at a power of $P_{\mathrm{MW}} = -132$ dBm at the input port of the cavity.

On-demand generator of a traveling cat state with superconducting circuits

Hayato Goto[1], Zhirong Lin[2], Tsuyoshi Yamamoto[2,3], Yasunobu Nakamura[2,4]

[1]*Frontier Research Laboratory, Corporate Research&Development Center, Toshiba Corporation, 1, Komukai-Toshiba-cho, Saiwai-ku, Kawasaki 212-8582, Japan*

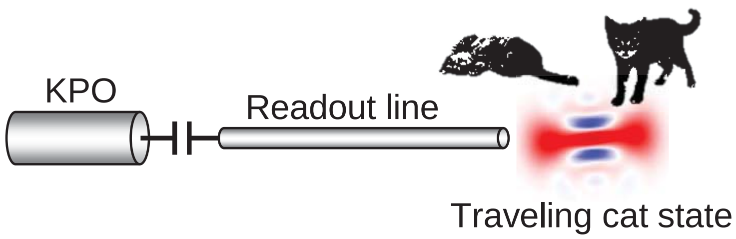
[2]*RIKEN Center for Emergent Matter Science (CEMS), Wako, Saitama 351-0198, Japan*

[3]*IoT Devices Research Laboratories, NEC Corporation, Tsukuba, Ibaraki 305-8501, Japan*

[4]*Research Center for Advanced Science and Technology (RCAST), The University of Tokyo, Meguro-ku, Tokyo 153-8904, Japan*

A Schödinger cat state, which is a quantum superposition of two coherent states, is one of the most intriguing states in quantum physics. Experimental realization of the cat state has been reported with various physical systems. However, *deterministic* generation of a *traveling* cat state had not been demonstrated experimentally until the recent experiment with superconducting circuits [1], which is based on controlled release of a cat state generated inside a cavity.

Here we propose another simple method of on-demand generation of a traveling cat state. This is based on the recent proposal of deterministic generation of a cat state with a Kerr parametric oscillator (KPO) [2,3]. In the previous proposals, the KPO is assumed to be lossless in ideal cases, and therefore the cat state is confined inside the KPO. In the present work, we theoretically study a KPO coupled to a one-dimensional external system (readout line), where the coupling strength is assumed constant. We found that a traveling cat state can be generated on demand with an appropriately controlled pump rate. We also examine superconducting-circuit implementation of this idea.



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P-09

Exponentially-Enhanced Light-Matter Interaction, Cooperativities, and Steady-State Entanglement Using Parametric Amplification

Wei Qin,[1,2] Adam Miranowicz,[2,3] Peng-Bo Li,[2,4] Xin-You Lü,[5]
J.-Q You,[1] and Franco Nori[2,6]

[1]*Beijing Computat. Sci. Res. Ctr., Beijing 100193, China*
[2]*CEMS, RIKEN, Wako-shi, Saitama 351-0198, Japan*
[3]*Fac. Phys., Adam Mickiewicz Univ., 61-614 Poznań, Poland*
[4]*Dept. Appl. Phys., Xi'an Jiaotong Univ., Xi'an 710049, China*
[5]*Sch. Phys., Huazhong Univ. Sci. & Technol., Wuhan 430074, China*
[6]*Dept. Phys., Univ. Michigan, Michigan 48109-1040, USA*

We propose an experimentally-feasible method for enhancing the atom-field coupling as well as the ratio between this coupling and dissipation (i.e., cooperativity) of two atoms in an optical cavity. Our approach also enables the generation of steady-state nearly-maximal quantum entanglement. It exploits optical parametric amplification [see Fig. 1(a)] to exponentially enhance the atom-cavity interaction [see Fig. 1(b)] and, hence, the cooperativity of the system, with the squeezing-induced fluctuation noise being completely eliminated. Thus, an effective cooperativity much larger than 100 can be achieved even for modest values of a squeezing parameter. We demonstrate that the entanglement infidelity is exponentially smaller than the lower bound on the infidelities obtained in other dissipative entanglement preparations without applying squeezing. Thus, this infidelity can be arbitrarily small. Our generic method for enhancing atom-cavity cooperativities can be implemented in a wide range of physical systems, and provides diverse applications for quantum information processing based on entanglement.

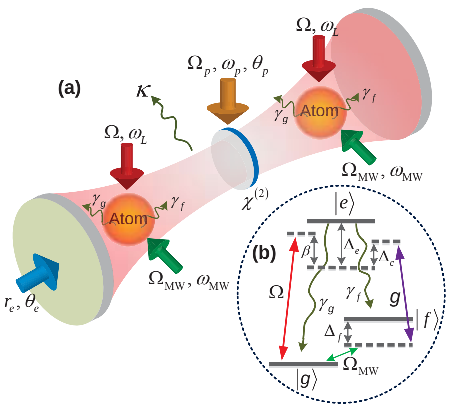

Fig.1. (a) Two driven atoms are trapped inside a single-mode cavity, which contains a nonlinear medium and couples to a squeezed-vacuum reservoir. (b) Level structure of the atoms and the transitions driven by a laser (Ω), a microwave (Ω_{MW}), and the cavity mode (g).

Reference: arXiv 1709.09555v1.

Quantum optics with giant artificial atoms in a 1D waveguide

Anton Frisk Kockum[1,*], **Göran Johansson**[2], **and Franco Nori**[1,3]
[1] *Center for Emergent Matter Science, RIKEN, Saitama 351-0198, Japan*
[2] *MC2, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden*
[3] *Physics Department, The University of Michigan, Ann Arbor, Michigan 48109-1040, USA*
E-mail: anton.frisk.kockum@gmail.com

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, superconducting qubits coupled to a meandering transmission line, or to surface acoustic waves [1, 2, 3], can realize "giant artificial atoms" that couple to a bosonic field at several points which are wavelengths apart [4, 5]. Here, we study setups with multiple giant atoms coupled at multiple points to a one-dimensional (1D) waveguide [6]. We show that the giant atoms can be protected from decohering through the waveguide, but still have exchange interactions mediated by the waveguide. Unlike in decoherence-free subspaces, here the entire multi-atom Hilbert space is protected from decoherence. This is not possible with "small" atoms. We further show how this decoherence-free interaction can be designed in setups with multiple atoms to implement, e.g., a 1D chain of atoms with nearest-neighbor couplings (Fig. 1) or a collection of atoms with all-to-all connectivity. This may have important applications in quantum simulation and quantum computing.

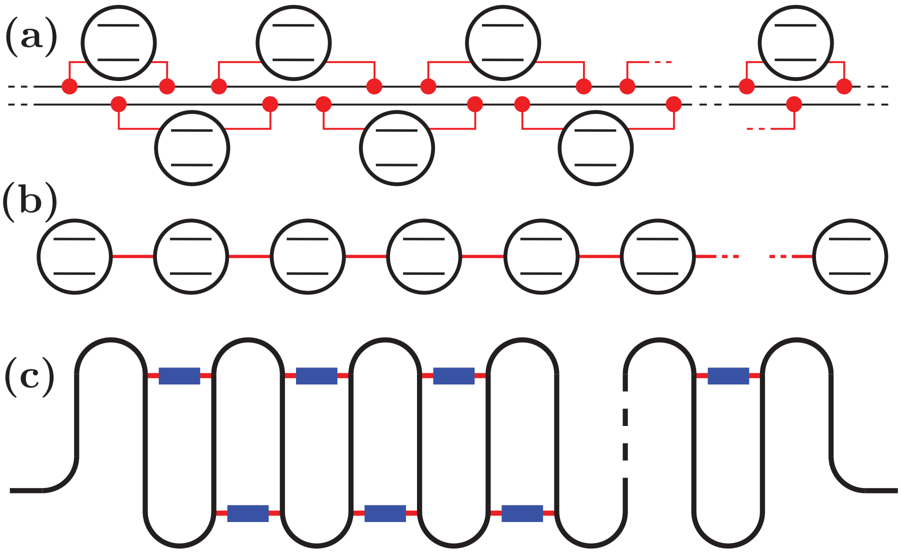

Figure 1: (a) Layout of the connection points for the giant atoms. (b) The effective system. (c) An implementation with superconducting circuits. The black line is a transmission line, the blue blocks are qubits, and the red lines mark where the qubits couple to the transmission line.

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P-11

Multi-mode Quantum Rabi Model and Superluminal Signalling

Carlos Sánchez Muñoz[1], Franco Nori[1,2], and Simone De Liberato[3]
[1] CEMS, RIKEN, Saitama, 351-0198, Japan
[2]Department of Physics, University of Michigan, Ann Arbor, MI 48109-1040, USA
[3] School of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, United Kingdom
E-mail: email@somewhere (11 point)

Recent technological developments have made it increasingly easy to access the non-perturbative regimes of cavity-QED known as ultra or deep strong coupling, where the light-matter coupling becomes comparable to the bare modal frequencies [1,2]. In this work, we address the adequacy of the broadly used single-mode Rabi model to describe such regimes. We demonstrate that, in the non-perturbative light-matter coupling regimes, the Rabi model becomes unphysical, allowing for superluminal signalling. Moreover, we show that the multi-mode description of the electromagnetic field, necessary to account for light propagation at finite speed, yields physical observables that differ radically from their single-mode counterpart already for moderate values of the coupling. Our multi-mode analysis also reveals phenomena of fundamental interest on the dynamics of the intracavity electric field, where a free photonic wavefront and a bound state of virtual photons are shown to coexist.

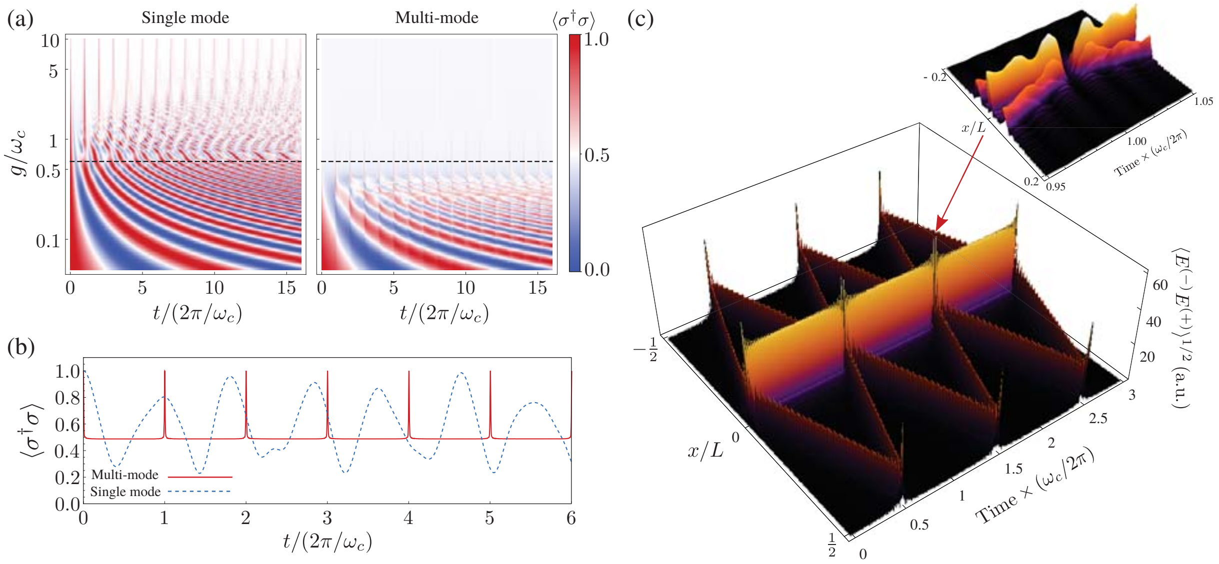

Figure 1: (a) Contour plot of the 2LS population as a function of time and coupling rate. (b) Evolution of the population of an initially excited 2LS for the single-mode (blue, dashed) and multi mode (red, solid) cases, for a coupling rate of $g/\omega_c = 0.6$ (c) Amplitude of the electric field inside the cavity as a function of space and time, for $g/\omega_a = 0.6$.

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Observing pure effects of counter-rotating terms without ultrastrong coupling: A single photon can simultaneously excite two qubits

Xin Wang (12 point)
Institute of Quantum Optics and Quantum Information,
School of Science, Xi'an Jiaotong University, Xi'an 710049, China

The coherent process that a single photon simultaneously excites two qubits has recently been theoretically predicted by [Phys. Rev. Lett. 117, 043601 (2016)]. We propose a different approach to observe a similar dynamical process based on a superconducting quantum circuit, where two coupled flux qubits longitudinally interact with the same resonator. We show that this simultaneous excitation of two qubits (assuming that the sum of their transition frequencies is close to the cavity frequency) is related to the counter-rotating terms in the dipole-dipole coupling between two qubits, and the standard rotating-wave approximation is not valid here. By numerically simulating the adiabatic Landau-Zener transition and Rabi-oscillation effects, we clearly verify that the energy of a single photon can excite two qubits via higher-order transitions induced by the longitudinal couplings and the counter-rotating terms. Compared with previous studies, the coherent dynamics in our system only involves one intermediate state and, thus, exhibits a much faster rate. We also find transition paths which can interfere. Finally, by discussing how to control the two longitudinal coupling strengths, we find a method to observe both constructive and destructive interference phenomena in our system.

P-13

PIQS – Permutational Invariant Quantum Solver

Nathan Shammah[1], Shahnawaz Ahmed[2,1], Neill Lambert[1], Simone De Liberato[3], and Franco Nori[1,4]

[1] *RIKEN, Wako-shi, Saitama 351-0198, Japan*

[2] *Birla Institute of Technology and Science, Pilani–Goa, India*

[3] *School of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, United Kingdom*

[4] *Department of Physics, University of Michigan, Ann Arbor, Michigan 48109-1040 , USA*

E-mail: nathan.shammah@riken.jp

PIQS – Permutational Invariant Quantum Solver is an open-source computational library in Python for the study of the dynamics of open quantum systems [1]. Permutational invariance is applied to simplify the exact numerical treatment of Lindblad master equations, exponentially reducing the matrix size scaling, from $O(2^N)$ to $O(N^3)$ or $O(N^2)$ for special but interesting cases [2]. The open quantum system simulation includes the action of spontaneous emission, nonradiative losses, dephasing, incoherent pumping, collective pumping, and collective dephasing. We provide the salient features of *PIQS* and report some applications to superradiant light emission with dephasing, steady-state superradiance and spin squeezing. Thanks to an easy-to-use API and a collection of built-in functions, *PIQS* allows the user to readily study a variety of many-body quantum systems composed of a collection of two-level systems. The initial states can be any Dicke state – including non-symmetrical Dicke states – thermal states, the GHZ state, and coherent spin states, among others. Moreover, *PIQS* is benchmarked against other recent libraries exploiting permutational invariance and the relation of the underlying numerical methods implemented is also discussed. By implementing *PIQS* on a commercial personal computer with standard characteristics we report the investigation of the full density matrix of over $N = 1000$ two-level systems. *PIQS* and the physics described here fall in the development of new methods to support the study of cavity QED and that of condensed matter physics, e.g., enabling future investigations of driven-dissipative open quantum systems and their phase transitions out of equilibrium.

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Anomalous conductance in a strongly interacting Fermi gas

Shun Uchino[1] and Masahito Ueda[1,2]
[1]*CEMS, RIKEN*
[2]*Department of Physics, The University of Tokyo*

A strongly interacting Fermi gas realized with ultracold atoms has attracted attention due to similarities to neutron stars and high-Tc superconductors. A new aspect of studies in such a system is to understand its nonequilibrium dynamics. Recently, the so-called two-terminal system with a strongly interacting Fermi gas has been realized by the ETH group.

Here, we discussed mesoscopic conduction properties of such a gas through a quantum point contact. In the superfluid regime, a nonlinear current-bias characteristics that originates from multiple Andreev reflections can be seen. In addition, conduction properties in the non-superfluid regime turn out to be nontrivial. We show that the current contribution originating from preformed pairs is essential near the critical temperature of the Fermi superfluid.

Study on the squeezed microwave photon prepared by a Josephson parametric amplifier

Gahyun Choi,[1,2] Taewan Noh,[1] Katarina Cicak,[3] Florent Lecocq,[3] José Aumentado,[3] Kibog Park,[2] Woon Song,[1] and Yonuk Chong[1]

[1]Korea Research Institute of Standards and Science (KRISS), Daejeon 34113, Korea

[2]Ulsan National Institute of Science and Technology (UNIST), Ulsan 44919, Korea

[3]National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA

Josephson parametric amplifier (JPA) is a representative nonlinear resonator that can be used to generate the squeezed state in the regime of microwave frequency. We performed a homodyne measurement to detect the fluctuation of the power of photon field generated by JPA operating in the degenerate mode, from which we could infer its quantum state. We constructed a density matrix from the phase-dependent distribution by using maximum likelihood estimation and observed that the population resides only in the even photon number states, which indicates the generation of squeezed photon field. We also studied the interaction between a qubit and a squeezed photon field in a three dimensional circuit QED system.

Ultrastrong coupling regime of two-photon interactions

Simone Felicetti
Laboratoire Matériaux et Phénomènes Quantiques,
Université Paris Diderot, CNRS UMR 7162, Sorbonne Paris Cité, France

Two-photon interaction (TPI) processes have so far been considered only as arising from second- or higher-order effects in driven systems, and so limited to extremely small coupling strengths. However, a variety of novel physical phenomena emerges in the strong or ultrastrong coupling regime, where such coupling values become comparable to dissipation rates or to the system bare frequencies, respectively. In the ultrastrong coupling regime of TPIs a spectral collapse [1] can take place, i.e. the system discrete spectrum can collapse in a continuous band. Furthermore, in the many-body limit, TPIs are characterized by a rich interplay between the spectral collapse and the superradiant phase transition [2]. The physics of TPI models can be simulated using atomic systems [3,4], however the implementation of two-photon couplings in an undriven system requires an interaction more complex than dipolar.

In this contribution, I will present a superconducting circuit scheme able to implement a nondipolar ultrastrong interaction between a flux qubit and a microwave resonator [5]. An open quantum system analysis of a TPI model shows that fundamental quantum optical phenomena are qualitatively modified with respect to standard dipolar interactions. We find that realistic parameters allow to reach the spectral collapse, where extreme nonlinearities are expected to emerge at the few-photon level.

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P-17

Exploring the dispersive regime of quantum magnonics

Dany Lachance-Quirion[1,2], Yutaka Tabuchi[1], Atsushi Noguchi[1], Rekishu Yamazaki[1], Yasunobu Nakamura[1,3]

[1] *Research Center for Advanced Science and Technology, University of Tokyo, Meguro-ku, Tokyo 153-8904, Japan.*

[2] *Institut quantique and Dpartement de Physique, Universit de Sherbrooke, Sherbrooke, Qubec J1K 2R1, Canada.*

[3] *Center for Emergent Matter Science, RIKEN, Wako, Saitama 351-0198, Japan.*

E-mail: yasunobu@qc.rcast.u-tokyo.ac.jp

Combining different physical systems in hybrid quantum circuits opens up novel possibilities for quantum technologies. In quantum magnonics, quanta of collective excitation modes in a ferromagnet, called magnons, interact coherently with qubits to enable accessing quantum phenomena of magnons. Here, we use this architecture to probe quanta of collective spin excitations in a millimeter-sized ferromagnetic crystal. More specifically, we resolve magnon number states through spectroscopic measurements of a superconducting qubit with the hybrid system in the strong dispersive regime (Figs. **A** to **C**) [1]. Furthermore, we use this strong dispersive interaction to probe magnon relaxation through measurements of the Husimi Q function of magnon coherent states (Fig. **D**). The observed relaxation time $T_1 = 350$ ns is much longer than expected from the magnon linewidth of 1.3 MHz (Fig. **E**). This observation, combined with an observed Gaussian decay of the magnon population (Fig. **E**), indicates the presence of a mechanism inducing pure dephasing which significantly increases the magnon linewidth in the quantum regime.

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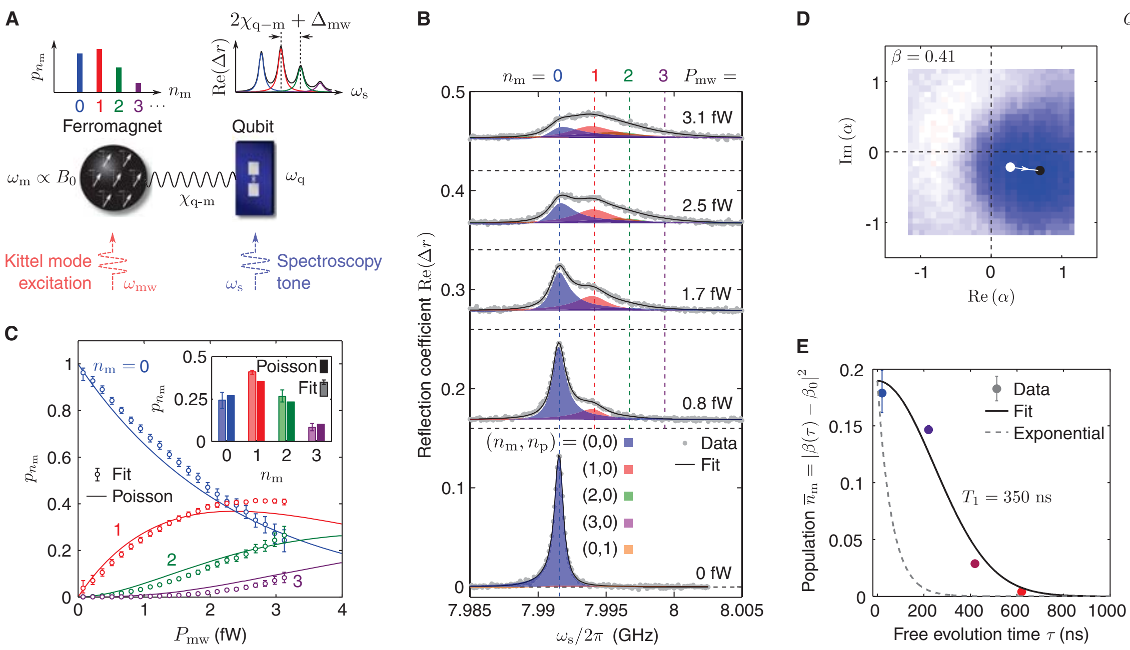

Tunable Quantum Hyperbolic Metamaterial Using Nitrogen-Vacancy Centers in Diamond

Qing Ai[1,2], Peng-Bo Li[1,3], Wei Qin[1,4], C. P. Sun[4], F. Nori[1,5]

1 CEMS, RIKEN, Wako-shi, Saitama 351-0198, Japan

2 Physics Dept., Beijing Normal University, Beijing 100875, China

3 Applied Physics Dept., Xi'an Jiaotong University, Xi'an 710049, China

4 Beijing Computational Science Research Center, Beijing 100193, China

5 Physics Dept., The University of Michigan, Ann Arbor, Michigan 48109-1040, USA

We show that nitrogen-vacancy (NV) centers in diamond can produce a novel quantum hyperbolic metamaterial. We demonstrate that a hyperbolic dispersion relation in diamond with NV centers can be engineered and dynamically tuned by applying a magnetic field. This quantum hyperbolic metamaterial with a tunable window for the negative refraction allows for the construction of a super-lens beyond the diffraction limit.

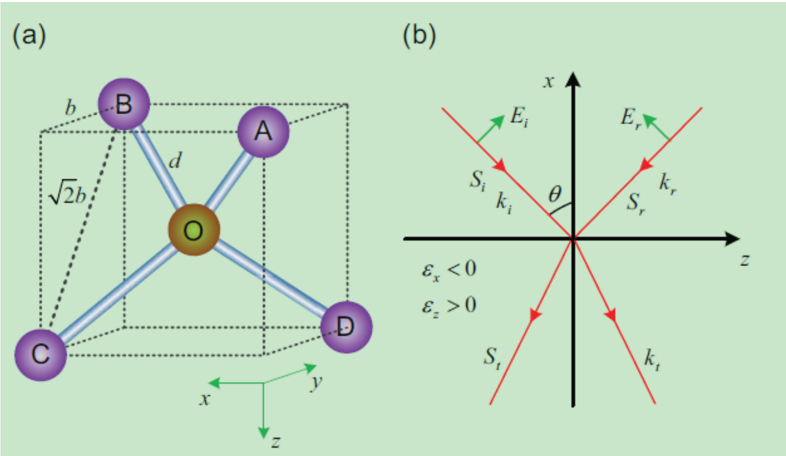

Fig. 1: (a) The four possible orientations of NV centers in diamond. (b) Negative refraction at the interface between diamond and air.

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Disorder-induced dephasing in backscattering-free quantum transport

Clemens Gneiting[1] **and Franco Nori**[1,2]
[1] *Quantum Condensed Matter Research Group, RIKEN, Saitama 351-0198, Japan*
[2] *Department of Physics, University of Michigan, Ann Arbor, Michigan 48109-1040, USA*
E-mail: clemens.gneiting@riken.jp

The possibility of backscattering-free transport in topological insulators renders them promising candidates for applications in quantum information processing, where reliable transmittance of quantum states is a prerequsite for successful implementations. However, even though edge states are robust against backscattering, they are not immune to disorder effects when it comes to dephasing, as described by a disorder-induced deformation of states. This poses a potential obstacle to their successful deployment as carriers of quantum information. Here, we present our analysis of such disorder-induced dephasing. Employing a quantum master equation description, we are able to quantify the time evolution of disorder-perturbed edge mode states. Based on this, we can show that the disorder-induced dephasing remains bound. Moreover, we identify a gap condition to remain in the backscattering-free regime between the bulk bands.

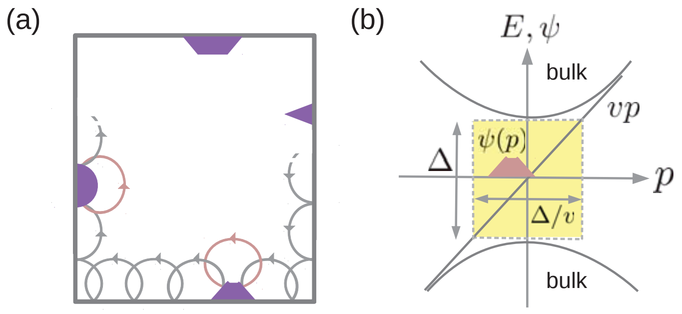

Figure 1: Backscattering-free propagation. (a) Quasiclassical representation of skipping orbits in a quantum Hall sample in the presence of a strong magnetic field. Because of the directional Lorentz-force bending of the orbits, obstacles/impurities cannot reverse the direction of motion. (b) Generic band model of a topological insulator. Edge modes exist in the bulk band gap of width Δ. To propagate backscattering-free, edge mode wave packets must remain confined in the gap region.

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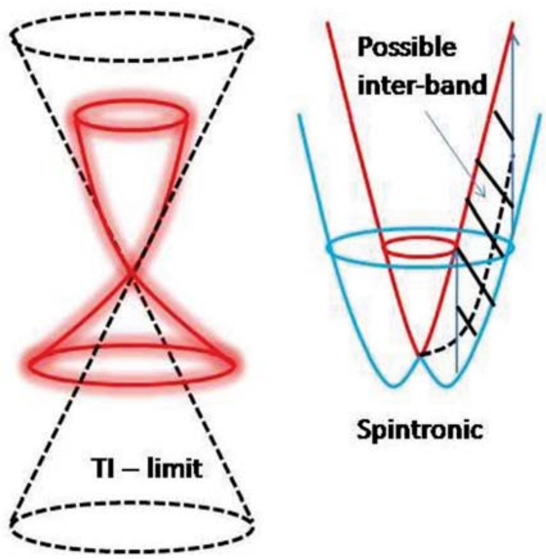
Magneto-optical conductivity of topological spintronics: nonlinear nonreciprocal effects

Zhou Li

RIKEN

The Fermi velocity associated with the spin-orbit coupling is two orders of magnitude smaller for spintronic semiconductors than it is for topological insulators. Both families can be treated with the same Hamiltonian which contains a relativistic (Dirac) linear in momentum term proportional to v_F and a non-relativistic quadratic contribution with an effective mass (m). We find that the AC dynamic longitudinal and transverse (Hall) magneto-conductivities are strongly dependent on the size of v_F. When the Dirac fermi velocity is small, the absorption background provided by the interband optical transitions is finite only over a very limited range of photon energies as compared with topological insulators. The magnetic field will break the time reversal symmetry and the system is non-reciprocal. If the magnetic field is turned off and the inversion symmetry was broken, one can expect an all-electric version of this nonlinear nonreciprocal phenomena.



Wiring superconducting quantum circuits to phononic crystals

Patricio Arrangoiz-Arriola, E. Alex Wollack, Zhaoyou Wang, Marek Pechal, Nathan R. Lee, Jeremy D. Witmer, Jeff T. Hill, and Amir H. Safavi-Naeini

Department of Applied Physics and Ginzton Laboratory

Stanford University

Over the past decade, a growing number of experiments have demonstrated coupling of superconducting circuits to mechanical degrees of freedom, enabling new hybrid devices for the study of acoustic waves in the quantum regime. Recently these have included propagating as well as localized surface and bulk acoustic waves on piezoelectric substrates, where it is possible to achieve strong, resonant coupling with superconducting charge qubits. Here we propose a new platform based on thin-film lithium niobate on silicon (LNOS), where all circuit layers rest on a low-loss, passive silicon substrate and the lithium niobate film serves as a two-dimensional functional layer in which we pattern all nanomechanical structures. We discuss a computational technique to calculate the coupling strength to arbitrary mechanical structures and show that reaching the strong-coupling regime should be possible with modest microwave and mechanical losses. Finally, we present preliminary experimental results on a one-dimensional phononic crystal defect cavity coupled to a flux-tunable SQUID-array resonator.

Information Retrieval and Criticality in Parity-Time-Symmetric Systems

Kohei Kawabata[1], Yuto Ashida[1], and Masahito Ueda[1, 2]
[1] *Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[2] *RIKEN Center for Emergent Matter Science, Wako, Saitama, 351-0198, Japan*

Parity-time (PT) -symmetric open systems [1] have recently attracted considerable attentions in many disciplines of physics such as optics [2], atomic physics [3], and optomechanics [4]. PT-symmetric systems exhibit unconventional phase transitions accompanying exceptional points that have no analogue in closed systems. While there has been growing interest in understanding behavior of PT-symmetric open quantum systems [5], the information-theoretic aspect of PT-symmetric systems has yet to be explored.

In this study [6], we investigate information flow between a general PT-symmetric system and an environment. We find that the complete information retrieval from the environment can be achieved in the PT-symmetry-unbroken phase, while no information can be retrieved in the PT-symmetry-broken phase. The PT-transition point thus marks the reversible-irreversible criticality of information flow, around which many physical quantities such as the recurrence time and the distinguishability between quantum states exhibit power-law behavior. Moreover, by embedding a PT-symmetric system into a larger closed system, we reveal that the information retrieval originates from an effective finite-dimensional environment, which is a universal feature of the PT-symmetry-unbroken open quantum systems.

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Discrete Time-Crystalline Order in Cavity and Circuit QED Systems

Zongping Gong[1], Ryusuke Hamazaki[1], and Masahito Ueda[1,2]
[1]*Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[2]*RIKEN Center for Emergent Matter Science (CEMS), Wako, Saitama 351-0198, Japan*

Discrete time crystals are a recently proposed [1-3] and experimentally observed [4,5] out-of-equilibrium dynamical phase of Floquet systems, where the stroboscopic evolution of a local observable repeats itself at an integer multiple of the driving period. We address this issue in a driven-dissipative setup [6], focusing on the modulated open Dicke model, which can be implemented by cavity or circuit QED systems [7,8]. In the thermodynamic limit, we employ semiclassical approaches and find rich dynamical phases on top of the discrete time-crystalline order. In a deep quantum regime with few qubits, we find clear signatures of a transient discrete time-crystalline behavior, which is absent in the isolated counterpart. We establish a phenomenology of dissipative discrete time crystals by generalizing the Landau theory of phase transitions to Floquet open systems.

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Loop-gap Microwave Resonator for Hybrid Quantum Systems

Jason R. Ball,[1] Yu Yamashiro,[1,2] Hiroshi Sumiya,[3] Shinobu Onoda,[4] Takeshi Ohshima,[4] Junichi Isoya,[5] Denis Konstantinov,[1] and Yuimaru Kubo[1,6]

[1)] *Okinawa Institute of Science and Technology Graduate University, Onna, Okinawa 904-0495, Japan*

[2)] *Department of Physics, University of the Ryukyus, Nishihara, Okinawa 903-0213, Japan*

[3)] *Sumitomo Electric Industries Ltd., Itami, Osaka 664-001, Japan*

[4)] *Takasaki Advanced Radiation Research Institute, National Institutes for Quantum and Radiological Science and Technology, Takasaki, Gunma 370-1292, Japan*

[5)] *Research Center for Knowledge Communities, University of Tsukuba, Tsukuba, Ibaraki 305-8550, Japan*

[6)] *PRESTO, JST, Kawaguchi, Saitama 332-0012, Japan*

We designed a loop-gap microwave resonator for applications of spin-based hybrid quantum systems, and tested it with impurity spins in diamond. Strong coupling with ensembles of nitrogen-vacancy (NV) centers as well as nitrogen (P1) centers were observed. The external coupling rate can be tuned by changing the depth of the microwave SMA antenna pins.

Electrical detection of spin-polarized local and non-local current in topological insulator $Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$

Tae-Ha Hwang[1], Hong-Seok Kim[1], Sang-Il Park[1], Hoil Kim[2,3], Jun Sung Kim[2,3] and Yong-Joo Doh[1†]

[1] Department of Physics and Photon Science, Gwangju Institute of Science and Technology, Gwangju 61005, Korea

[2] Center for Artificial Low Dimensional Electronic Systems, Institute for Basic Science, Pohang 37673, Republic of Korea

[3] Department of Physics, Pohang University of Science and Technology, Pohang 37673, Republic of Korea

† Correspondence to: yjdoh@gist.ac.kr

KEYWORDS: topological insulator, spin-momentum locking, electrical spin detection, nonlocal

Abstract

Spin-momentum locked (SML) topological surface state (TSS) provides an exotic property for spintronics applications of topological insulators (TIs). The spin-polarized current due to SML can be directly detected using spin potentiometric measurement. In this report, we electrically measure spin polarization ratio of $Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$ which is a low-doped topological insulator. Ferromagnetic Co contact was chosen intentionally to minimize interfacial band bending at the interface, at which the spin-dependent potentiometric measurement takes place. The spin voltage was measured as a function of the current bias, temperature, and gate voltage. We also report, for the first time in our best knowledge, a spin-potentiometric measurement using non-local spin-polarized current, which is unique property of TI. The polarization ratio is obtained to be $p = 0.036$ (0.183) for local (non-local) measurement, respectively. The higher spin polarization ratio obtained from the non-local current is attributed to reduction of bulk carrier contribution. Our observations provide highly enhanced way to determine spin-polarization ratio, which is inherent in the TSS in TI.

Superconducting quantum interference device of $(Bi_{1-x}Sb_x)_2Se_3$ topological insulator nanoribbons

Nam-Hee Kim[1], Hong-Seok Kim[1], Bongkeon Kim[1], Yiming Yang[2], Xingyue Peng[2], Dong Yu[2], Yong-Joo Doh[1*]

[1]Department of Physics and Photon Science, School of Physics and Chemistry, Gwangju Institute of Science and Technology (GIST), Gwangju 61005, Korea
[2]Department of Physics, University of California, Davis, CA 95616, U.S.A.

Topological insulators(TIs) with topologically protected surface states are fascinating materials for detecting the Majorana fermion when coupled with a superconductor. Since the Majorana fermion has charge neutrality and zero energy, the superconducting quantum interference devices(SQUIDs) are received attention. The SQUID is very sensitive to a magnetic flux, so it plays a crucial role for a superconducting flux qubit. Here, we report fabrication and electrical transport properties of SQUIDs, made from a $(Bi_{1-x}Sb_x)_2Se_3$ topological insulator nanoribbon(NR) connected with $Pb_{0.5}In_{0.5}$ superconducting electrodes. A TI NR is transferred onto a SiO_2/Si while the $Pb_{0.5}In_{0.5}$ electrodes are deposited using electron-beam lithography and electron-beam deposition techniques. Below the transition temperature of the superconducting $Pb_{0.5}In_{0.5}$ electrodes, periodic oscillations of the critical current are observed in the TI NR SQUID with a magnetic field applied perpendicular to the plane due to the flux quantization. Moreover, the envelope of the voltage modulation of the SQUID shows Fraunhofer-like patterns of each single junction.

Aharonov-Bohm oscillations in $(Bi_{1-x}Sb_x)_2Se_3$ topological insulator nanoribbon

Hong-Seok Kim [1], Nam-Hee Kim [1], Yiming Yang [2], Xingyue Peng [2],
Dong Yu [2], Yong-Joo Doh [1]*

[1] *Department of Physics and Photon Science, Gwangju Institute of Science and Technology (GIST), Gwangju, 61005, Korea*

[2] *Department of Physics, University of California, Davis, CA 95616, USA*

The 0- and π-phase Aharonov-Bohm (AB) oscillations have been theoretically predicted in one-dimensional (1D) topological insulators (TIs). Here, we report the experimental observations of highly coherent AB oscillations in $(Bi_{1-x}Sb_x)_2Se_3$ TI nanoribbon with varying temperature, gate voltage and channel length. Temperature dependence of the AB oscillations can be understood by a thermal broadening effect of 1D subbands of the topological surface state. When the channel length increases, the observed AB oscillations resemble a disorder-induced dephasing effect of the density of states. Our experimental results provide a direct evidence that the topologically-protected surface states are quantized along the TI nanoribbon circumference and form 1D subbands to exhibit a unique quantum electronic transport properties.

Quantum Criticality and the Tomonaga-Luttinger Liquid in One-Dimensional Bose Gases

Yong-Guang Zheng[1,3], Bing Yang[1,3,*], Yang-Yang Chen[2,*], Hui Sun[1,3], Han-Ning Dai[1,3], Xi-Wen Guan[2,†], Zhen-Sheng Yuan[1,3], Jian-Wei Pan[1,3]

[1]*Hefei National Laboratory for Physical Sciences at Microscale and Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui 230026, China*

[2]*State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, China*

[3]*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany*

[*]*These authors contributed equally to this work.*

[†]*E-mail: xiwen.guan@anu.edu.au*

The low-energy physics of one-dimensional (1D) strongly correlated systems is generally described by the Tomonaga-Luttinger liquid (TLL) regardless of quantum statistics of the constituent particles. Such collective behaviour results in the free-fermion universality class of quantum criticality near a phase transition. Although evidences for the TLL have been found in a variety of 1D materials, a conclusive observation of the hallmark TLL and criticality remains challenging due to the lack of proper measures and the requirement of extreme experimental conditions. Here we report an observation of quantum criticality and the TLL in a system of ultracold ^{87}Rb atoms within 1D tubes. The universal scaling laws are measured precisely and the characteristic critical temperatures are determined by the double-peak structure of specific heat, confirming the existence of three phases: classical gas, quantum critical region and the TLL. The Luttinger parameter estimated from the observed sound velocity approaches the measured Wilson ratio (WR), which reveals the collective nature of the TLL and the quantum fluctuations. The experimental results are in excellent agreement with the predictions from the Yang-Yang grand canonical theory. Our method paves a way to directly explore diverse critical phenomena and quantum liquids involving rich spin and charge interactions in ultracold atoms and condensed matters.

Variational principle for quantum impurity systems in and out of equilibrium

Yuto Ashida[1], Tao Shi[2], Mari Carmen Bañuls[2], J. Ignacio Cirac[2] and Eugene Demler[3]
[1]*Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[2]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse. 1, 85748 Garching, Germany*
[3]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*

Out-of-equilibrium phenomena in quantum many-body systems have become a fascinating field of active research, as motivated by recent experimental developments in ultracold gases and nanosystems such as quantum dots, molecular electronics and carbon nanotubes. Quantum spin impurity models (SIM) as typified by the Kondo model are among the most fundamental paradigms of such strongly correlated systems. They have proven crucial to understanding non-Fermi liquid behavior in heavy fermion materials and transport phenomena in mesoscopic systems and given theoretical foundations of dynamical mean-field theory (DMFT).

In this work, we present a versatile variational approach to studying ground-state properties and spatiotemporal dynamics in a broad class of SIM [1]. The difficulty in SIM stemmed from the need to treat the strong entanglement between the impurity and bath. We introduce a new canonical transformation that can completely disentangle the impurity from bath degrees of freedom. We combine it with Gaussian states to formulate a family of variational states, which can efficiently encode the nontrivial correlations in SIM. We apply our approach to the prototypical Kondo models and study their real-time dynamics, universal nonperturbative scaling and transport phenomena. Some of the results are challenging to obtain in other theoretical approaches, and can be experimentally tested with mesoscopic electron systems such as quantum dots and ultracold atoms in optical lattices [2].

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Quantum electronic transport in InAs semiconductor nanowire

Rak-Hee Kim*, Nam-Hee Kim*, Hong-Seok Kim*, Jindong Song**, Yong-Joo Doh*

* Department of Physics and Photon Science, School of Physics and Chemistry, Gwangju Institute of Science and Technology (GIST), Gwangju 61005, Korea

** Korea Institute of Science and Technology, Seoul 02792, Korea

InAs nanowire provides a useful platform for developing high-mobility quantum electronic devices. In particular, the InAs nanowires, grown by high vacuum molecular beam epitaxy, exhibit conductance quantization behavior at low temperature, which is a signature of quasi one-dimensional (1D) electronic transport. When the magnetic field is applied, the spin degeneracy in the 1D subbands can be lifted due to the Zeeman effect. The strong spin-orbit interaction in InAs also can induce spin splitting of conduction subbands. Those electronic properties are essential to build 1D topological superconducting system in the nanowire. Here we report quantum electronic transport properties of InAs nanowire with varying gate voltage, temperature and magnetic field.

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Quantum electronic transport in $(Bi_{1-x}Sb_x)_2Se_3$ topological insulator nanoribbon contacted with superconducting electrodes

Heungsoon Im*, Nam-Hee Kim*, Hong-Seok Kim*, Yasen Hou**, Rui Xiao**, Dong Yu**, Yong-Joo Doh*

* Department of Physics and Photon Science, School of Physics and Chemistry, Gwangju Institute of Science and Technology (GIST), Gwangju 61005, Korea

** Department of Physics, University of California, Davis, CA 95616, USA

The formation of spin-textured metallic edge states in topological insulators (TIs) enables highly coherent charge and spin transport. Combinations of TIs with conventional superconductors can also provide useful platforms for creating and manipulating emergent particles such as Majorana fermions, which are essential for topological quantum computers. Here, we report electronic transport properties of $(Bi_{1-x}Sb_x)_2Se_3$ TI nanoribbon at low temperatures. With the magnetic field applied parallel to the nanoribbon axis, Aharonov-Bohm conductance oscillations were observed. In the superconducting state below the superconducting transition temperature of Al electrodes, the conductance enhancement due to Andreev reflection was observed.

Towards non-destructive, real-time transport measurements of interacting fermions

Hideki Konishi, Kevin E. Roux, Barbara Cilenti and Jean-Philippe Brantut

Institute of Physics, École Polytechnique Fédérale de Lausanne
E-mail: hideki.konishi@epfl.ch

Transport is a fundamental process occurring typically for electrical charges in materials or nano-electronic devices, where it underlies most of the application of these systems. Its non-equilibrium nature, however, makes it difficult to numerically simulate and understand the emergence and evolution of transport. In recent years, it has become possible to investigate transport phenomena using cold atoms trapped in optical potentials in the manner of quantum simulations. Previous researches have indeed realized the Landauer setup [1] and a quantum point contact [2] and observed quantized conductance [3] emerging in mesoscopic systems.

Since the detection method implied so far the destructive observation of atom number densities, measurements relied on comparing different samples. This makes the measurements sensitive to even very weak fluctuations in the atomic sample preparation. In order to achieve more precise measurements, it is highly desirable to follow the flow of atoms in a single realization of the experiment, which requires a non-destructive probing way. For this purpose, we plan to implement quantum non-demolition measurements of the atomic current featuring cavity quantum electrodynamics for fermionic lithium-6 with a high-finesse optical cavity. We will continuously monitor either the change of atom numbers in one of the terminal reservoirs or motions of atoms within mesoscopic transport channels [4] by phase sensitive detection of the cavity field. In the poster we will detail the non-destructive probing scheme and present the design of the experimental apparatus and the current status of the experiment.

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Nuclear-spin-induced edge resistance in two-dimensional topological insulators

Chen-Hsuan Hsu[1], Peter Stano[1], Jelena Klinovaja[1,2], and Daniel Loss[1,2]

[1]*RIKEN Center for Emergent Matter Science (CEMS), Japan*

[2]*Department of Physics, University of Basel, Switzerland*

We investigate the effects of the nuclear spins on the edge resistance of a two-dimensional topological insulator (2DTI) [1]. The nuclear spins couple to the edge-state electrons via the hyperfine interaction. In the disordered phase, randomly oriented nuclear spins allow elastic spin-flip backscattering of the edge electrons (Figure). At sufficiently low temperatures, on the other hand, the nuclear spins may form an order [2-6], as a result of the RKKY interaction mediated by the edge electrons. We demonstrate that such ordering induces an internal magnetic field, and causes the field-assisted backscattering on charge impurities, in addition to the magnon-mediated backscattering. We perform the renormalization-group analysis to investigate the resistance resulting from these backscattering mechanisms. Finally, we take InAs/GaSb 2DTI as an example to make estimation on the edge resistance, as well as the experimental conditions where a resistance becomes significant.

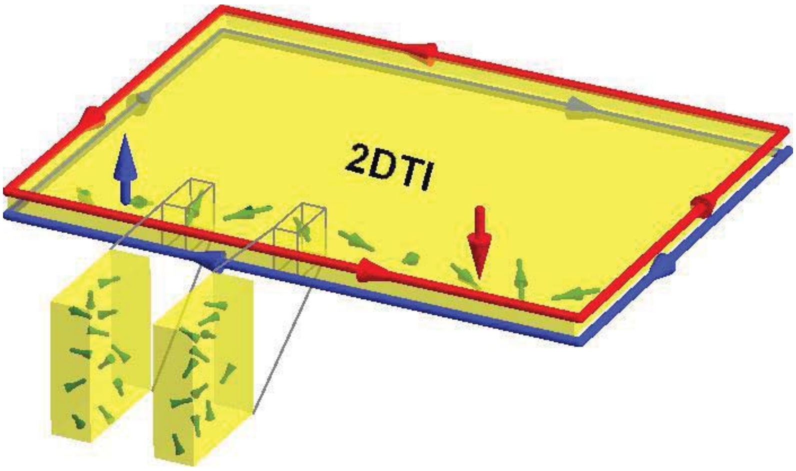

Figure: The up-spin (blue) and down-spin (red) electrons counter-propagate along the edges of a 2DTI (yellow). The nuclear spins (green) in the host material can lead to the spin-flip backscattering of the edge electrons.

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Optimizing bath properties of a dark-state-enhanced photosynthetic heat engine

Melina Wertnik[1,2], Neill Lambert[1], Alex Chin[3], and Franco Nori[1,4]

1) CEMS, RIKEN, Wako-shi, Saitama 351-0198, Japan

2) ETH Zurich, CH-8093 Zurich, Switzerland

3) Cavendish Laboratory, University of Cambridge

4) Department of Physics, University of Michigan, USA

We analyze the role of coherent, non-perturbative system-bath interactions in a photosynthetic [1] heat engine model [2,3]. Using the reaction-coordinate formalism [4,5] to describe the vibrational phonon-environment in the engine, we analyze the efficiency around an optimal parameter regime predicted in earlier works. We show that, in the case of concentrated photon illumination, the phonon-assisted population transfer between bright and dark states is suppressed due to dephasing from the photon environment.

Manipulating the phonon bath properties via its spectral density enables us to identify both optimal low- and high-frequency regimes where the suppression can be removed. This suppression of transfer suggests that it is important to consider carefully the non-perturbative effects of system-bath environments in designing artificial photosynthetic systems, and that these interactions provide a new “lever” by which to optimize such systems.

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Fractional quantization of the charge and spin transport in 1D topological quantum pumps

Pasquale Marra
Quantum System Theory Research Team, Center for Emergent Matter Science, RIKEN, Saitama, Japan

One-dimensional quantum pumps have been recently realized in optical lattices. These systems exhibit a distinctive fractal energy spectra, the Hofstadter butterfly, and show a topologically non-trivial phase-space where the topological invariant coincides with the quantized charge or spin pumped at each pumping cycle. The quantization is analogous to the quantum Hall effect and to the spin quantum Hall effect. The charge or the spin transferred in a fraction of the pumping period is instead generally not quantized. We show, however, that due to the specific symmetries of these systems, the charge and the spin transferred at well-defined fractions of the pumping period is quantized as integer fractions of the Chern number. This fractional quantization is topological in nature and it is a direct consequence of the symmetries of the system, and does not rely on the presence of interactions.

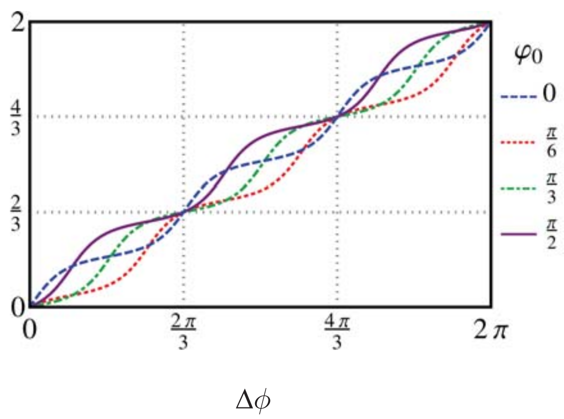

Fig. 1: Charge transferred as a function of the phase variation $\Delta\phi$.

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Shortcuts to adiabatic cat-state generation in Bose-Einstein condensates

Takuya Hatomura
Department of Physics, The University of Tokyo
E-mail: hatomura@spin.phys.s.u-tokyo.ac.jp

Cat states, which are superpositions of macroscopically distinct states, consisting of large number of atomic particles have not been observed in experiments yet, while technological progress in ultra-cold atomic physics is significant [1]. One of the obstacles to generating cat states is decoherence due to particle losses. In order to avoid this problem, we have to consider stable and fast processes against particle losses. In general, schemes relying on the adiabatic theorem are stable against decoherence. However, the adiabatic theorem requires long time to accomplish schemes when number of particles N becomes large, which leads to losing large number of particles. One of the possible candidates overcoming this difficulty is shortcuts to adiabaticity [2]. In counter-diabatic driving, which is one of the methods of shortcuts to adiabaticity, we can mimic adiabatic dynamics in finite time by adding the control Hamiltonian which cancels out diabatic changes. Note that applying counter-diabatic driving exactly to quantum many-body systems is generally difficult and thus some approximation is usually considered.

We propose approximated counter-diabatic driving in bosonic Josephson junctions, which consist of two-mode Bose-Einstein condensates [3]. Here, we apply the Holstein-Primakoff transformation with finite-size corrections, which prevent divergence of schedules of counter-diabatic driving at the critical point. Schedules of the counter-diabatic driving consist of three steps. The first step is the counter-diabatic driving in the disordered phase. The second one is smoothly and slowly approaching the critical point. The last one is the counter-diabatic driving in the ordered phase. Using the counter-diabatic driving, adiabatic generation of cat states is successfully accelerated. The enough large quantum Fisher information ensures that generated cat states are highly entangled.

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Chiral quantum network based on lambda-type emitter coupled to waveguide

Tao Li[1], **Adam Miranowicz**[1,2], **Xuedong Hu**[1,3], **Keyu Xia**[1,4], **and Franco Nori**[1,5]
[1]*CEMS, RIKEN, Saitama 351-0198, Japan*
[2]*Faculty of Physics, Adam Mickiewicz University, 61-614 Poznań, Poland*
[3]*Department of Physics, University at Buffalo, SUNY, Buffalo, New York 14260, USA*
[4]*College of Engineering and Applied Sciences, Nanjing University, Nanjing 210008, China*
[5]*Physics Department, The University of Michigan, Ann Arbor, Michigan 48109-1040, USA*
E-mail: tao.li.fv@riken.jp

Quantum networks hold great promise for absolutely secure information transfer due to its exploitation of fantastic characters of quantum physics [1]. In a practical quantum network, photons, interacting weakly with their environment, are natural candidates for quantum data bus, connecting remote quantum processors and quantum memories. The effective interface [2] between flying photons and stationary emitters is therefore a prerequisite for the building of quantum networks.

Here we propose an interface for chiral quantum networks [3]. A lambda-type atom coupled to a nano-waveguide provides a direction-dependent single photon scattering, and it is exploited to constitute a chiral building block for quantum networks. Quantum-state swapping and hybrid-entanglement generation between a single polarized photon and a single atom are implemented in the same building block [3]. Interestingly, the building block switches its functions by tuning the transition frequency of the atom, and, in principle, could be performed deterministically for either function. Furthermore, the building block works efficiently even when a polarized photon of wide bandwidth is involved, and the direction-dependent character of this building block provides more probability for the development of complex quantum networks [1–5].

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Characterization of one-dimensional topologically ordered states via multipartite entanglement in dual lattice

Yu-Ran Zhang[1,2], **Yu Zeng**[3], **Heng Fan**[3], **J. Q. You**[2,1], **and Franco Nori**[1,4,*]
[1] *CEMS, RIKEN, Saitama 351-0198, Japan*
[2] *Beijing Computational Science Research Center, Beijing 100094, China*
[3] *Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China*
[4] *Physics Department, University of Michigan, Ann Arbor, Michigan 48109-1040, USA*
[*] *E-mail: fnori@riken.jp*

Multipartite entanglement plays a key role in quantum physics and quantum metrology, and moreover, it is central to the understanding of quantum many-body systems. We demonstrate that multipartite entanglement is able to characterize one-dimensional topological order, which is witnessed by the the scaling behavior of the quantum Fisher information of the ground state with respect to the spin operators defined in the original and dual lattices. We investigate an exactly-solvable long-range extended spin-$\frac{1}{2}$ Ising model with nontrivial $\mathbf{Z}$-symmetry topological order identified by winding numbers and paired Majorana zero modes at each end. For topologically ordered phases with high winding numbers, we can define a $\mathbf{Z}$ topological invariant by the scaling coefficient of the dual quantum Fisher information density. Containing richer properties and more complex structures than bipartite entanglement, the dual multipartite entanglement of the topologically ordered state has promising applications in robust quantum computation and quantum metrology and could be generalized to higher-dimensional systems.

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Supercurrent Interference in Few-Mode Nanowire Josephson Junctions

Kun Zuo[1,2], Vincent Mourik[1,2,3], Daniel B. Szombati[1,2,4,5], Bas Nijholt[2], David J. van Woerkom [1,2,6], Attila Geresdi[1,2], Jun Chen[7], Viacheslav P. Ostroukh[8], Anton R. Akhmerov[2], Sebastin R. Plissard[2,9], Diana Car[1,2,9], Erik P. A. M. Bakkers[1,2,9], Dmitry I. Pikulin[10,11,12], Leo P. Kouwenhoven[1,2,13], and Sergey M. Frolov[2,7]

[1] *QuTech, Delft University of Technology, 2600 GA Delft, The Netherlands*
[2] *Kavli Institute of Nanoscience, Delft University of Technology, 2600 GA Delft, The Netherlands*
[3] *Centre for Quantum Computation and Communication Technologies, School of Electrical Engineering and Telecommunications, UNSW Sydney, Sydney, New South Wales 2052, Australia*
[4] *Australian Research Council Centre of Excellence for Engineered Quantum Systems, St Lucia, Queensland 4072, Australia*
[5] *School of Mathematics and Physics, University of Queensland, St Lucia, Queensland 4072, Australia*
[6] *Department of Physics, ETH Zurich, CH-8093 Zurich, Switzerland*
[7] *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, USA*
[8] *Instituut-Lorentz, Universiteit Leiden, P.O. Box 9506, 2300 RA Leiden, The Netherlands*
[9] *Department of Applied Physics, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands*
[10] *Station Q, Microsoft Research, Santa Barbara, California 93106-6105, USA*
[11] *Department of Physics and Astronomy, University of British Columbia, Vancouver BC, Canada V6T 1Z1*
[12] *Quantum Matter Institute, University of British Columbia, Vancouver BC, Canada V6T 1Z4*
[13] *Station Q Delft, Microsoft Research, 2600 GA, Delft, The Netherlands*
E-mail: kun.zuo@riken.jp

Junctions created by coupling two superconductors via a semiconductor nanowire in the presence of high magnetic fields are the basis for the potential detection, fusion, and braiding of Majorana bound states. We study NbTiN/InSb nanowire/NbTiN Josephson junctions and find that the dependence of the critical current on the magnetic field exhibits gate-tunable nodes. This is in contrast with a well-known Fraunhofer effect, under which critical current nodes form a regular pattern with a period fixed by the junction area. Based on a realistic numerical model we conclude that the Zeeman effect induced by the magnetic field and the spin-orbit interaction in the nanowire are insufficient to explain the observed evolution of the Josephson effect. We find the interference between the few occupied one-dimensional modes in the nanowire to be the dominant mechanism responsible for the critical current behavior. We also report a strong suppression of critical currents at finite magnetic fields that should be taken into account when designing circuits based on Majorana bound states.

Brillouin scattering of optical vortices by magnetic quasi-vortices

A. Osada[1], A. Gloppe[2], R. Hisatomi[2], A. Noguchi[2], R. Yamazaki[2],
M. Nomura[1], Y. Nakamura[2,3], and K. Usami[2]

[1]*Institute of Industrial Science (IIS), The University of Tokyo*

[2]*Research Center for Advanced Science and Technology (RCAST), The University of Tokyo*

[3]*Center for Emergent Matter Science (CEMS), RIKEN*

Vortex-like excitations, characterized by orbital angular momenta (OAM), have been one of the central objects of research in physics, where the interaction between vortices is governed by the OAM conservation. In the recently emerging field of cavity optomagnonics, ferromagnetic spheres made of yttrium iron garnet (YIG), which is transparent in infrared wavelength, have been investigated as a canonical platform [1-4]. In a YIG sphere, optical whispering gallery modes (WGMs) play a role of *optical vortices* and magnetostatic modes, or Walker modes, carry the *magnetic quasi-vortices*. However, previous experimental studies exclusively focused on the spatially uniform magnetostatic mode with zero OAM.

Here we experimentally observe Brillouin scattering of light in WGMs by Walker modes with various OAM, which result in different behaviors as shown in Fig.1. These can be understood by the theory of Brillouin scattering involving spin and orbital angular momentum conservation. The orbital degree of freedom makes the system of cavity optomagnonics applicable to new chiral optic or topological photonic elements as well as enhancing the light-magnon interaction assisted by an optical resonator.

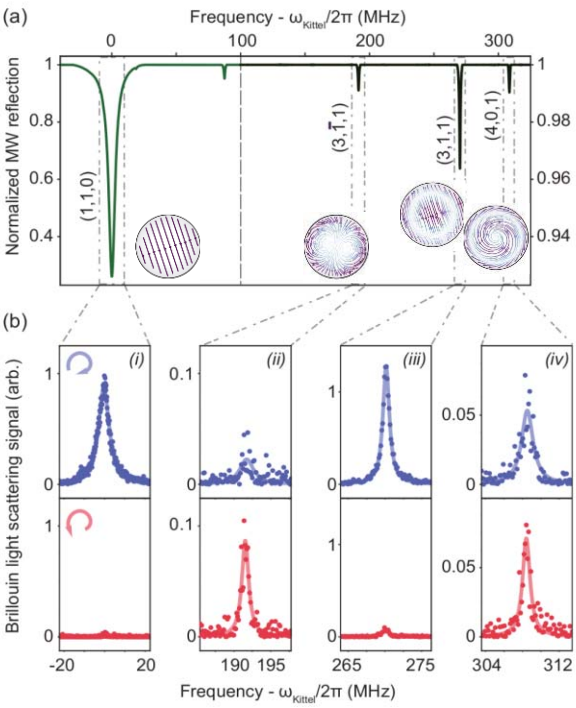

Fig.1 (a) Ferromagnetic resonance in a YIG sphere. (b) Nonreciprocal/reciprocal Brillouin scattering signals for various Walker modes.

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Quantum non-demolition detection of an itinerant microwave photon

Shingo Kono[1], Kazuki Koshino[2], Yutaka Tabuchi[1], Atsushi Noguchi[1], and Yasunobu Nakamura[1,3]

[1] *Research Center for Advanced Science and Technology (RCAST), The University of Tokyo, Meguro-ku, Tokyo 153-8904, Japan*
[2] *College of Liberal Arts and Sciences, Tokyo Medical and Dental University, Ichikawa, Chiba 272-0827, Japan and*
[3] *Center for Emergent Matter Science (CEMS), RIKEN, Wako, Saitama 351-0198, Japan*
E-mail: s.kono@ap.t.u-tokyo.ac.jp

Photon detectors are an elementary tool to measure electromagnetic waves at the quantum limit and are heavily demanded in the emerging quantum technologies such as communication, sensing, and computing. Of particular interest is a quantum non-demolition (QND) type detector, which projects the quantum state of a photonic mode onto the photon-number basis without affecting the temporal or spatial properties. This is in stark contrast to conventional photon detectors which absorb a photon to trigger a 'click' and thus inevitably destroy the photon. The long-sought QND detection of a flying photon was recently demonstrated in the optical domain using a single atom in a cavity [1].

Microwave quantum optics in superconducting circuits enables us to investigate unprecedented regimes of quantum optics. The strong nonlinearity brought by Josephson junctions together with the strong coupling of the qubits with resonators/waveguides reveals rich physics not seen in the optical domain before. However, single photon detection in the microwave domain is still a challenging task because of the photon energy four to five orders of magnitude smaller than in optics. Note that QND measurements of cavity-confined microwave photons have been realized by using a Rydberg atom or a superconducting qubit as a probe [2,3].

Here, we experimentally demonstrate a QND detection of an itinerant microwave photon using a circuit quantum electrodynamics architecture with a transmon qubit in a largely detuned 3D cavity. When an itinerant photon is reflected by the cavity, it interacts dispersively with the qubit. With an appropriate adjustment of the cavity bandwidth, the qubit deterministically acquires the phase flip after the reflection, which corresponds to a controlled-Z gate between the itinerant photon and the superconducting qubit. With a single-shot measurement of the phase flip of the qubit, we detect the single photon without destroying it. We achieve a QND detection of a single photon with the quantum efficiency of 0.84, the photon survival probability of 0.87, and the dark-count probability of 0.0147. We also demonstrate a heralded single-photon extraction from a coherent microwave pulse with the fidelity of 0.84.

Our scheme can be a building block for quantum networks connecting distant qubit modules as well as a microwave photon counting device for multiple-photon signals.

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Magnetically induced transparency of a quantum metamaterial composed of twin flux qubits

K. V. Shulga[1,5,6,8], **E. Il'ichev**[2], **M. V. Fistul**[1,3,5], **I. S. Besedin**[1,5], **S. Butz**[4], **O. V. Astafiev**[5,6,7], **U. Hübner**[2] **and A. V. Ustinov** [1,4,5]
[1] *National University of Science and Technology MISIS, 119049 Moscow, Russia*
[2] *Leibniz Institute of Photonic Technology, PO Box 100239, D-07702 Jena, Germany*
[3] *Institute for Basic Science, Daejeon 34051, Republic of Korea*
[4] *Physikalisches Institut, Karlsruhe Institute of Technology, D-76131, Karlsruhe, Germany*
[5] *Russian Quantum Center, 119049 Moscow, Russia*
[6] *Moscow Institute of Physics and Technology, Dolgoprudny, 141700 Moscow region, Russia*
[7] *Royal Holloway, University of London, Egham, Surrey TW20 0EX, United Kingdom*
[8] *RIKEN Center for Emergent Matter Science (CEMS), Japan*
E-mail: kirill.shulga@riken.jp

Quantum metamaterials, media built from quantum objects acting as meta-atoms, promise to display novel light-matter interaction phenomena. Here we demonstrate the superconducting quantum metamaterial build of an array of meta-atoms, each consisting of a pair of superconducting loops coupled via a tunnel junction (twin flux qubit). By varying an external magnetic field, we detected strong variations of the metamaterial transparency that are explained by magnetic flux localization and tunneling between metastable states in the two-cell flux qubits forming the quantum metamaterial. The peculiarity of the twin qubit structure includes the possibility of a sharp $0 \rightarrow \pi$ transition of the Josephson junctions phases that leads to an abrupt suppression of the microwave transmission in a broad frequency range. We present a quantum model for the system behaviour, which is consistent with out measured data.

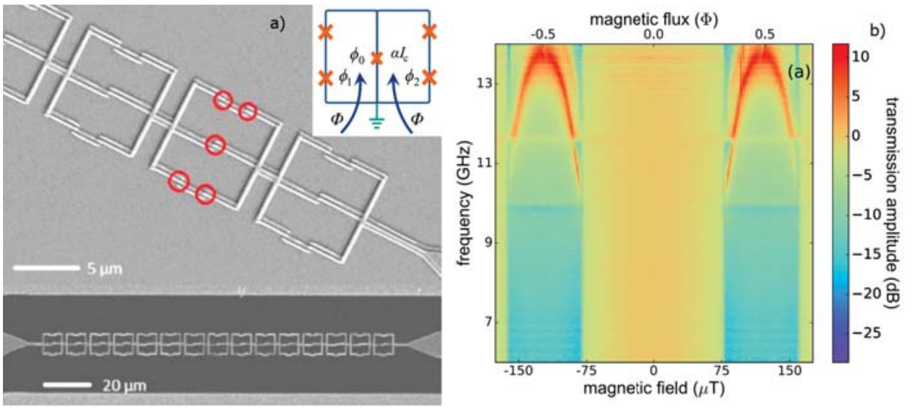

Figure 1: **a)** Superconducting quantum metamaterial consisting of an array of 15 twin qubits embedded in a coplanar wave guide. Each qubit consists of two superconducting loops sharing one common central Josephson junction (α-junction) and four identical Josephson junctions located on the outer parts of the loops. **b)** The measured dependence of the amplitude of transmission coefficient t on applied dc magnetic field and frequency f. The transmission t displays the sharp changes under variation of the magnetic flux Φ. One can see two different ranges of microwave propagation, nearly flat transmission around zero field and sharp resonant enhancement of the transmission near $11 - 14$ GHz at magnetic flux $\Phi \sim \pm\Phi_0/2$.

A two-qubit entangling gate between spin qubits of different kinds

A. Noiri[1], T. Nakajima[1], J. Yoneda[1], M. R. Delbecq[1], P. Stano[1], T. Otsuka[1], K. Takeda[1], S. Amaha[1], G. Allison[1], K. Kawasaki[2], A. Ludwig[3], A. D. Wieck[3], D. Loss[1,4], and S. Tarucha[1,2]

[1]*RIKEN, Center for Emergent Matter Science (CEMS), 2-1 Hirosawa, Wako-shi, Saitama, Japan*

[2]*Department of Applied Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan*

[3]*Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität Bochum, D-44780 Bochum, Germany*

[4]*Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland*

Electron spins in semiconductor quantum dots offer an attractive platform for quantum computing. So far, several kinds of spin qubits having their own advantages have been developed using different spin states [1,2]. In particular, high-fidelity qubit control has been demonstrated in single-spin qubits [3,4] while fast and high-fidelity initialization and readout have been realized in singlet-triplet (ST) qubits encoded in two-spin states [5]. However, the lack of an interface between different kinds of spin qubits impedes the integration of these advantages.

In this presentation, we realize a hybrid system of a single-spin qubit and a ST qubit in a GaAs-based triple quantum dot (TQD) with a micro-magnet and demonstrate a controlled-phase (CPHASE) gate between the two qubits. The single-spin qubit is defined on the left dot while the other two dots are operated as the ST qubit. The exchange interaction J between the two qubits shifts the qubit frequency of the target qubit depending on the state of the control qubit [6]. The rapid control of J enables us to implement CPHASE gate in 5 ns. These results are important step for realizing combined systems made out of spin qubits of different kinds, which provide a promising route to efficient spin-based quantum computing.

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Broadband flux-driven Josephson parametric amplifiers based on impedance engineering

Y. Urade[1], Z. R. Lin[1], T. Yamamoto[1,2], K. Inomata[1,3], and Y. Nakamura[1,4]
[1] *Center for Emergent Matter Science, RIKEN, Japan.*
[2] *IoT Devices Research Laboratories, NEC Corporation, Japan.*
[3] *National Institute of Advanced Industrial Science and Technology, Japan.*
[4] *Research Center for Advanced Science and Technology, The University of Tokyo, Japan.*
E-mail: yoshiro.urade@riken.jp

Josephson parametric amplifiers (JPAs), which can achieve quantum-limited low-noise amplification performance, are essential tools for sensitive cryogenic experiments such as quantum information processing based on superconducting circuits. Their operation principle is based on modulation of the nonlinear inductance of Josephson junctions [1, 2]. Drawbacks of conventional JPAs are their inherent small bandwidth and low saturation power, which are due to the resonator attached to Josephson junctions in order to enhance the nonlinear interaction. Recently, several methods have been proposed to overcome the drawbacks of conventional JPAs through environmental-impedance engineering, and a large bandwidth of hundreds of MHz has been achieved [3, 4]. These techniques utilize impedance-transforming circuits to engineer the environmental impedance seen by JPAs.

In this work, we apply the environmental-impedance-engineering technique [4] to flux-driven JPAs [2], whose SQUIDs are inductively pumped at the doubled frequency of the signal frequency. Flux-driven JPAs have advantages such as spatial and frequency separation of signal and pump tones. We consider a flux-driven JPA equipped with an auxiliary resonator for impedance compensation, as shown in Fig. 1. We show that the gain spectrum of the JPA becomes broad and flat by choosing the optimal impedance of the auxiliary resonator $Z_{\mathrm{aux}} = \sqrt{L_{\mathrm{aux}}/C_{\mathrm{aux}}}$.

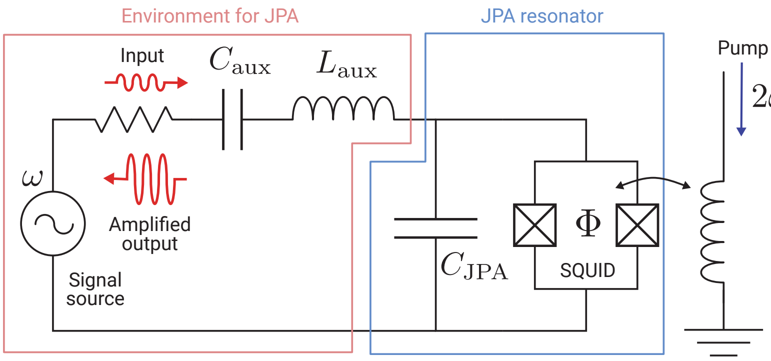

Figure 1: Schematic of a flux-driven JPA with an auxiliary resonator.

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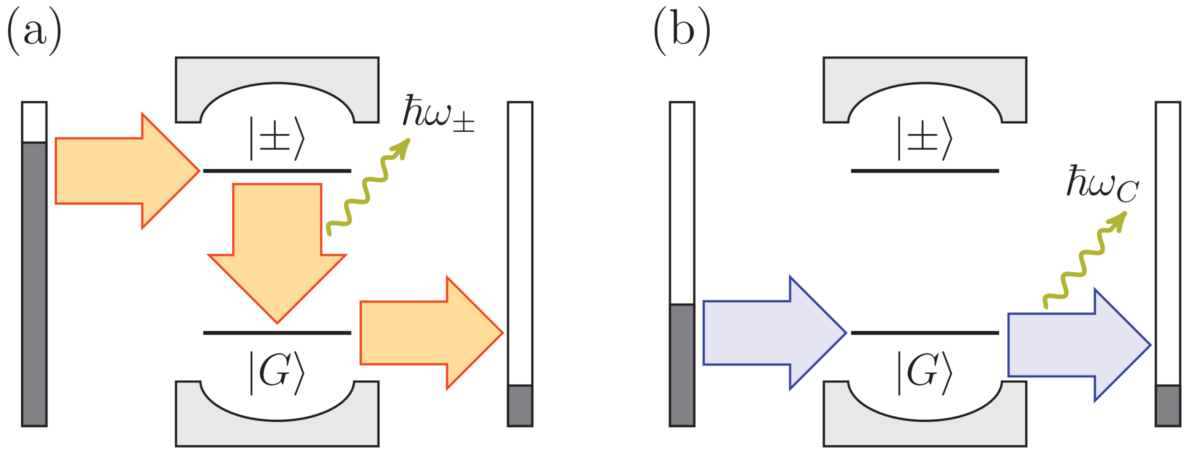
Ground State Eletroluminescence

Mauro Cirio[1], Simone De Liberato[2], Neill Lambert[1], and Franco Nori[1,3]
[1] *CEMS, RIKEN, Wako-shi, Saitama 351-0198, Japan*
[2] *School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, United Kingdom*
[3] *Department of Physics, University of Michigan, Ann Arbor, Michigan 48109-1040, USA*

Electroluminescence, the emission of light in the presence of an electric current, provides information on the allowed electronic transitions of a given system. It is commonly used to investigate the physics of strongly coupled light-matter systems, whose eigenfrequencies are split by the strong coupling with the photonic field of a cavity. In our work we showed that, together with the 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 the population of excited states followed by spontaneous emission, the process we describe extracts bound photons from the dressed ground state and it has peculiar features that unequivocally distinguish it from usual electroluminescence.



Schematics showing a light-matter system coupled to two electronic reservoirs.
(a) Standard electroluminescence emission. Electrons enter the system in an excited state which spontaneously decay emitting radiation.
(b) Ground state electroluminescence. Electrons enter the system in the ground state. When ultra-strongly coupled to the cavity field, electrons tunnelling out of the system can leave photons inside the cavity which eventually leak out.

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M. Cirio, S. De Liberato, N. Lambert, F. Nori, Ground State Electroluminescence, Phys. Rev. Lett. **116**, 113601 (2016).

Superconducting flux qubits embedded in a 3D cavity

S. Saito[1], I. Mahboob[1], H. Toida[1], Y. Matsuzaki[1], K. Kakuyanagi[1], W. J. Munro[1], Y. Nakamura[2,3], and H. Yamaguchi[1]

[1] *NTT Basic Research Laboratories, NTT Corporation, Kanagawa, 243-0198, Japan*

[2] *Research Center for Advanced Science and Technology, the University of Tokyo, Tokyo 153-8904, Japan*

[3] *Center for Emergent Matter Science, RIKEN, Saitama, 351-0198, Japan*

Superconducting qubits are one of the most promising candidates as a building block for quantum computers. A large effort has been made to improve their coherence properties. Recently a 3D cavity architecture has been developed to drastically elongate the coherence time of transmon qubits to 92 μs [1,2]. On the other hand, flux qubits were also improved using high quality shunt capacitors [3]. A coherence time of 85 μs has been observed. Combining both approaches may further enhance the coherence properties and so we have integrated a capacitively shunted flux qubit into a 3D cavity.

From the spectroscopy data fitting (Fig. 1), we obtain the Josephson energy of a typical junction as E_J = 190 GHz with a charging energy E_C = 2.35 GHz. The 3rd junction is $\alpha = 0.45$ times smaller than the typical junctions and the shunt capacitor is 50 fF. The qubit transition frequency at the optimal point ($\Phi_{qb} = 0.5\ \Phi_0$) is 5.0714 GHz and the flux qubit relaxation time is about 30 μs. In Figure 2 we plot the Ramsey decay time T_{2R} and echo decay time T_{2E} near the optimal point. Although the coherence times are shorter than 3D transmons or C-shunt flux qubits, we now have sufficent room to improve electromagnetic shielding and filtering of measurement lines. This work was supported by CREST, JST.

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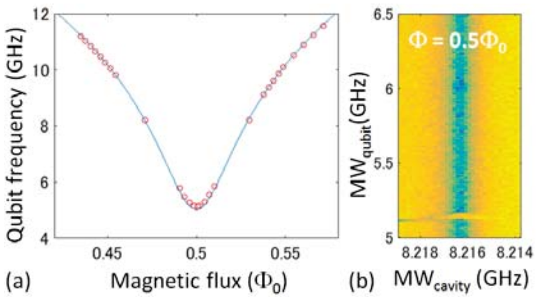


Fig. 1 (a) Qubit spectrum (b) Cavity reflection

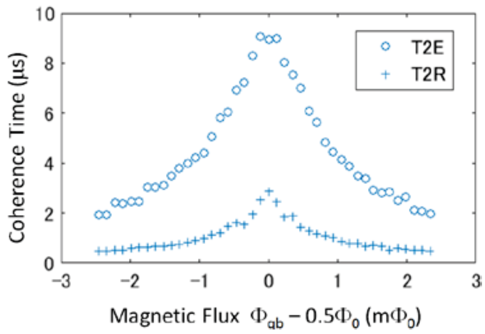


Fig. 2 Coherence times at around the optimal point

Conversion of environmental fluctuations to coherent fields by Cooper-pair box quantum meta-materials

I Lin Ho and Watson Kuo†
Department of Physics, National Chung Hsing University, Taichung 402, Taiwan
† *E-mail: wkuo@phys.nchu.edu.tw*

This work investigates transmission properties of electromagnetic fields propagating in open Cooper-Pair Boxes (CPBs) system. By using Lindblad master equation, we study effects of environments on this (artificial)atom-field system and give analytical solutions for Maxwell-Bloch equations. Implemented with a ring resonator and a Fabry-Perot cavity, numerical calculations show that: (1) With weak environmental couplings at superconductor phase operation, where the phase coupling energy (Josephson coupling) of CPBs is dominant, the system exhibits regular optical hysteresis. (2) With finite environmental couplings at superconductor charge operation, the Josephson effect and environmental effect can constructively interplay. On this condition, we found that the absorption coefficient of the fields can occur a small negative value, and indicates energy conversion from environments to coherent fields.

Hierarchy in temporal quantum correlations

H. Y. Ku,[1] S. L. Chen,[1] N. Lambert,[2] Y. N. Chen,[1, 2, 3], and F. Nori[2, 4]

[1]*Department of Physics, National Cheng Kung University, 701 Tainan, Taiwan*
[2]*CEMS, RIKEN, 351-0198 Wako-shi, Japan*
[3]*Physics Division, National Center for Theoretical Sciences, 300 Hsinchu, Taiwan*
[4]*Department of Physics, The University of Michigan, Ann Arbor, 48109-1040 Michigan, USA*

Einstein-Podolsky-Rosen (EPR) steering is an intermediate quantum correlation that lies in between entanglement and Bell non-locality. Its temporal analogue, temporal steering, has recently been shown to have applications in quantum information and open quantum systems. Here, we show that there exists a hierarchy among the three temporal quantum correlations: temporal inseparability, temporal steering, and macrorealism. Given that the temporal inseparability can be used to define a measure of quantum causality, similarly the quantification of temporal steering can be viewed as a weaker measure of direct cause and can be used to distinguish between direct cause and common cause in a quantum network.

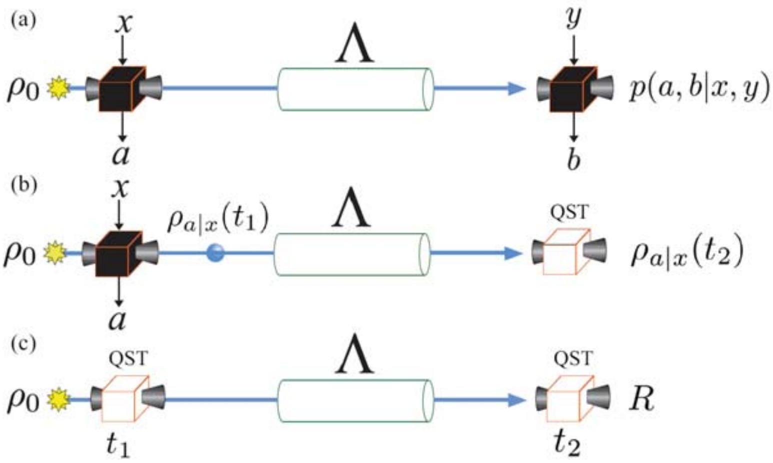


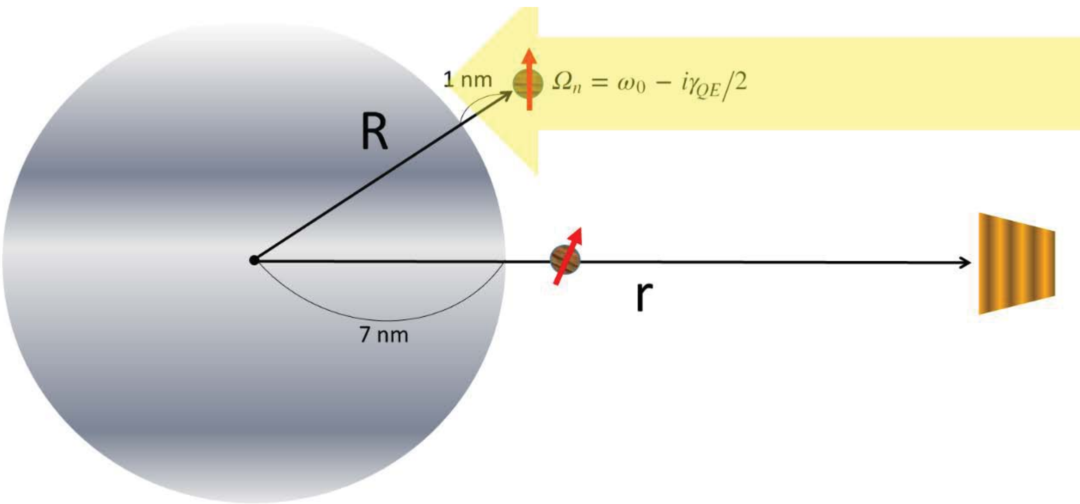
FIG. 1. Schematic diagram for (a) the temporal correlations scenario, (b) the temporal steering scenario, and (c) constructing the pseudo density matrix of a single system.

Dynamic of two quantum emitters coupled to localized surface plasmons

P. C. Kuo,[1], and Y. N. Chen,[1, 2]

[1]*Department of Physics, National Cheng Kung University, 701 Tainan, Taiwan*
[2]*National Center for Theoretical Sciences, 300 Hsinchu, Taiwan*

We theoretically study the dynamics of the energy transfer between two quantum emitters embedded inside a homogeneous dielectric with the coherent intermolecular dipole–dipole interactions involved. We show the controllable energy transfer by fine adjustment of transition dipole moment orientation. Owing to the sensitivity in distance between two quantum emitters, the dipole–dipole interactions decrease rapidly with distance and the energy transfer is suppressed. When the quantum emitters are placed close to a metal nanoparticle, a strong coupling between quantum emitters and the localized surface plasmons occurs, and the dynamics of quantum emitters is dramatically changed with the associated reversible exchange of energy. Therefore, our exploration opens new possibilities for the enhancement of energy transfer between the quantum emitters in long distance via the strong coupling to the localized surface plasmons.



$$\mathcal{H} = \int d^3\mathbf{r} \int_0^\infty d\omega \hbar\omega \hat{\mathbf{f}}^\dagger(\mathbf{r},\omega)\hat{\mathbf{f}}(\mathbf{r},\omega) + \sum_{n=1}^{N} \frac{\hbar\Omega_n}{2}\hat{\sigma}_n^z - \sum_{n=1}^{N}\left[\hat{\sigma}_n^+ + \hat{\sigma}_n^-\right]\boldsymbol{\mu}_n \cdot \left(\hat{\mathbf{F}}^{(+)}(\mathbf{r}) + \hat{\mathbf{F}}^{(-)}(\mathbf{r})\right)$$

polaritonic operators   fermionic operators

Hyperfine-phonon spin relaxation in a single-electron GaAs quantum dot

P. Stano[1,2,3], L. C. Camenzind[4], L. Yu[4], Ch.-H. Hsu[1], D. Loss[1,4], D. Zumbühl[4]

[1]*RIKEN, Center for Emergent Matter Science, 2-1 Hirosawa, Wako, Saitama, 351-0198, Japan*

[2]*Department of Applied Physics, School of Engineering, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 1113-8656, Japan*

[3]*RCQI, Institute of Physics, Slovak Academy of Sciences, 845 11 Bratislava, Slovakia*

[4]*Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland*

Understanding and control of the spin relaxation time T1 is among the key challenges for spin based qubits. A larger T1 is generally favored, setting the fundamental upper limit to the qubit coherence and spin readout fidelity. In GaAs quantum dots at low temperatures and high in-plane magnetic fields B, the spin relaxation relies on phonon emission and spin-orbit coupling. The characteristic dependence $T1{\sim}B^{-5}$ and pronounced B-field anisotropy were already confirmed experimentally. However, it has also been predicted 15 years ago that at low enough fields, the spin-orbit interaction is replaced by the coupling to the nuclear spins, where the relaxation becomes isotropic, and the scaling changes to $T1{\sim}B^{-3}$. We establish these predictions experimentally, by measuring T1 over an unprecedented range of magnetic fields -- made possible by lower temperature -- and report a maximum T1=57+-15s at the lowest fields, setting a new record for the electron spin lifetime in a nanostructure.

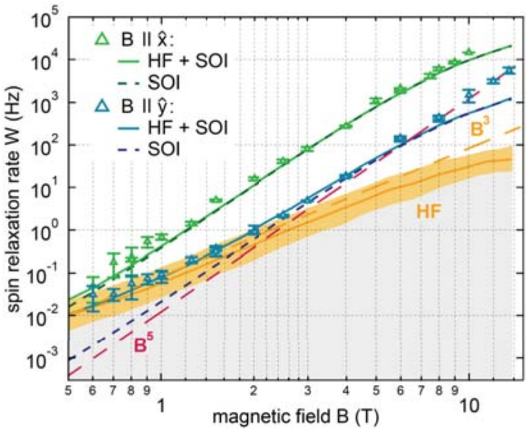


Figure: Single electron spin relaxation rate as a function of the magnetic field for two different directions (green and blue points). Lines are results of numerical simulations.

Reference: L. C. Camenzind, et al., (arxiv:1711.01474)

A 99.9%-fidelity spin qubit in isotopically purified silicon with charge-noise-limited coherence

J. Yoneda[1], K. Takeda[1], T. Otsuka[1], T. Nakajima[1], M. R. Delbecq[1], G. Allison[1], T. Honda[2], T. Kodera[2], S. Oda[2], Y. Hoshi[3], N. Usami[4], K. M. Itoh[5] and S. Tarucha[1]

[1]*RIKEN, 2-1 Hirosawa, Wako, Saitama, Japan*

[2]*Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo, Japan*

[3]*University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo, Japan*

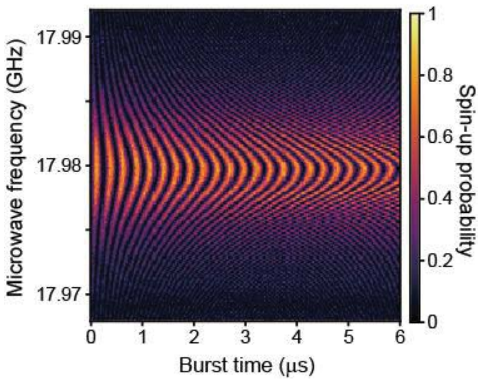
[4]*Nagoya University, Furocho, Chikusa-ku, Nagoya, Japan*

[5]*Keio University, 3-14-1 Hiyoshi, Yokohama, Japan*

Single electron spins in quantum dots is a promising candidate for semiconductor qubits, not least for potential scalability. Unlike charge, the spin degree of freedom is not intrinsically sensitive to electric noise, which opens up a path for high-fidelity control. In early developed GaAs devices, however, the ensemble phase coherence time T_2* was ~ 10 ns, due to the surrounding million nuclear spins. Later T_2* was extended to ~ 1 μs in silicon quantum dots, where 5% of the atoms carry nuclear spins naturally, and very recently T_2* ~ 30–120 μs has been achieved in isotopically purified materials (^{28}Si).

A complementary figure of merit relevant to the spin qubit fidelity is the manipulation time, T_π. T_π can be shortened by the strong spin-orbit coupling which mediates electrical spin control, naturally occurring in such materials as InAs and bent carbon-nanotubes. However, it has proven challenging to maintain a long T_2* when T_π is shortened; there exists a common tradeoff relation between the coherence and controllability.

This work[1] establishes a balance between coherence and controllability at a demanding, isotopically-enhanced level to achieve unprecedented performance of a quantum-dot spin qubit. We realize an artificial spin-orbit field with on-chip magnets for a single electron spin in a ^{28}Si/SiGe quantum dot. The extrinsic field is moderate enough to affect T_2* only marginally, but is large enough to T_π by two orders of magnitude. These figures of merit result in single-qubit control fidelity above 99.9%, which rivals the superconducting qubits for the first time with quantum dots. Surprising enough, we reveal that T_2* of such a high-fidelity spin qubit is no longer limited by nuclear spins but by 1/*f* charge noise.



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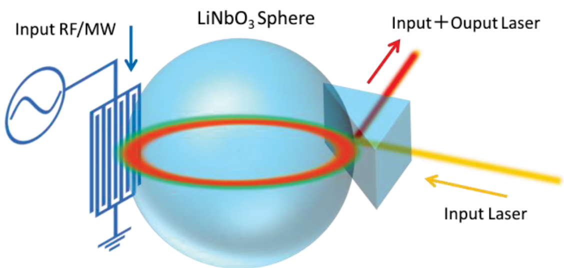
Optical-SAW Whispering Gallery Mode Resonator as an Optomechanical System

Rekishu Yamazaki[1, 2], Ayato Okada[1], Atsushi Noguchi[1, 2],
Yutaka Tabuchi[1], Koji Usami[1], Yasunobu Nakamura[1, 3]
1 Research Center for Advanced Science and Technology (RCAST), The University of Tokyo
2 PRESTO, Japan Science and Technology Agency
3 Center for Emergent Matter Science (CEMS), RIKEN

While many quantum systems have matured in its capability for control, some intrinsic characteristics are often burden for a further applicability. For example, while a rapid development of the superconducting circuits has made it one of the most promising candidates for the actualization of a large-scale quantum computer, the narrow bandgap of the superconductivity makes it impossible to directly couple the system to the optical photon, widely used for a long distance communication and the internet platform. A coupled quantum systems, forming a hybrid quantum system, can take advantages of different quantum systems to enhance its utility. Development of a hybrid quantum system, which enables a coherent bidirectional conversion between microwave and optical photons, so-called quantum transducer, is on call. The quantum transducer ensures coherent connections between quantum nodes and provides a foundation for the quantum information network.

For the coherent photon conversion, we are developing an optomechanical system with a surface acoustic wave (SAW). SAW is a wave localized on the surface of a solid and its various elastic effects enable coupling to different quantum systems. On our first device [1], a SAW resonator was formed on a lithium niobate ($LiNbO_3$) substrate. The RF applied on the circuit excites the SAW via piezo coupling and a laser was sent through the SAW standing wave, which impart a phase modulation on the laser via optoelastic coupling. We found limited conversion efficiency from the RF to optical signal due to a lack of overlap between the SAW and the optical mode. In this poster, we present a current effort to enhance the SAW-optical photon coupling by exploiting the whispering gallery mode (WGM) of the SAW as well as that of the optical photon on the $LiNbO_3$ sphere resonator. We find extremely high quality factor for both WGM. Selection rules for different coupling schemes are also discussed.



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Helical State in Ge/Si Core/Shell Nanowire

Jian Sun[1], Russell S. Deacon[1,2], Rui Wang[1], Jun Yao[3], Charles M. Lieber[3,4], Koji Ishibashi[1,2]

1. Advanced Device Laboratory, RIKEN, Japan 2. CEMS, RIKEN, Japan 3. Deparment of Chemistry and Chemical Biology, Harvard University, USA 4. School of Engineering and Applied Sciences, Harvard University, USA

E-mail: jian.sun@riken.jp

A helical state, exhibiting spin momentum locking, is predicted to emerge in 1D ballistic semiconductor nanowires (NWs) possessing strong Rashba spin-orbit interaction under an appropriate applied external magnetic field. Such a helical state is a key ingredient for the realization of Majarona zero modes [1], and has application for spin filtering [2], and Cooper pair splitters [3]. A distinct experimental signature of the helical state is a re-entrant conductance gap feature at the $2e^2/h$ conductance plateau as different portions of the band dispersion are probed. Recently the helical state has been experimentally detected in the lowest subband of InAs [4] and InSb [5] NWs. Hole systems offer several potential advantages for spintronics and quantum information processing application, having an effective spin of $J = 3/2$, momentum and spin are strongly coupled, enabling pure electric spin manipulation. Additionally, hole spin lifetimes can be significantly prolonged in the presence of confinement.

Here, we report the experimental measurement of helical hole states in a quantum point contact formed in a Ge/Si core/shell NW. Owing to a large valance band offset $\sim 0.5\,\mathrm{eV}$ between Ge and Si, holes are naturally accumulated in the Ge core and strongly confined by the interface with the Si shell [6]. The dopant-free growth leads to the high mobility with mean-free-path up to 500 nm. In addition, both Ge and Si lack nuclear spin which through hyperfine coupling is the typical leading contributer to the limit of spin coherence times for III-IV based qubit devices. More importantly, a strong dipole-coupled Rashba type SOI is predicted in Ge/Si NWs as a result of the quasi-degeneracy in its low energy valence bands [7], as such Ge/Si core/shell NWs are a promising material system to investigate helical hole states. The helical hole state is detected as a re-entrant conductance feature on conductance plateaus observed at integer multiples of $2e^2/h$. The helical spin-gap feature is confirmed by both magnetic field dependence and angular dependence, from which we can also extract a strong spin-orbit energy $E_{so} = 2.8\,\mathrm{meV}$ and large Landé g-factor of 4.7. They show good agreement with previous theoretical predictions [7] and our previous weak anti-localization measurements [8].

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Josephson emission of InAs nanowire Josephson junctions

H. Kamata[1, 2], R. S. Deacon[1, 3], S. Matsuo[2], K. Li[4], H. Q. Xu[4, 5],
K. Ishibashi[1, 3], and S. Tarucha[1, 2]
[1] *Center for Emergent Materials Science, RIKEN, Wako, Saitama, Japan*
[2] *Department of Applied Physics, University of Tokyo, Bunkyo, Tokyo, Japan*
[3] *Advanced Device Laboratory, RIKEN, Wako, Saitama, Japan*
[4] *Key Lab for the Physics and Chemistry of Nanodevices, Peking University, China*
[5] *Division of Solid State Physics, Lund University, Lund, Sweden*

InAs semiconductor nanowires (NWs), which exhibit a strong spin-orbit interaction and a large Landé g-factor, are good candidates for generating Majorana bound states (MBSs) in condensed matter when contacted to s-wave superconductors [1]. Observation of the 4π-periodic Josephson effect can be a strong evidence for MBSs, but still remains a challenge for NW-based topological systems because of the experimental difficulty. Here, we carry out direct measurement of rf emission spectra on NW-based Josephson junctions to investigate the 4π-periodic Josephson effect. In these junctions, emission spectra at half the Josephson frequency are predicted to appear in the topological regime.

A Josephson junction measured in this work has an InAs NW transferred to a gate dielectric of hexagonal boron nitride (h-BN) with NbTi/Al superconducting electrodes. The junction is connected to a coaxial line and decoupled from the dc measurement line via a bias-T. The Josephson emission radiated from the junction is amplified by cryogenic and room-temperature amplifiers and then measured with a spectrum analyzer.

As shown in Fig.1, we observe the emission spectra at the fundamental Josephson frequency f_J but not the 4π-periodic Josephson effect. Note in contrast to microwave spectroscopy measurements utilizing an on-chip detector, which is affected by the external magnetic field [3], our direct high frequency measurement will be more appropriate to investigate the excitation spectra in the high magnetic field regime or topological regime.

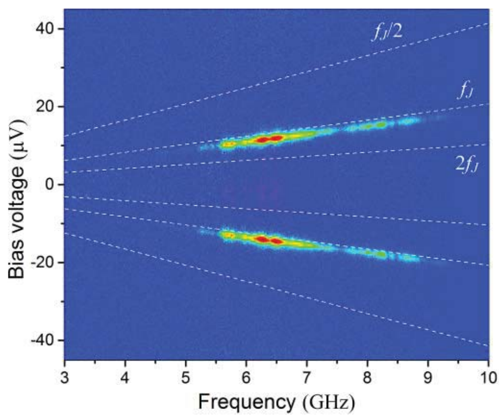

Fig.1: Emission spectra observed at zero magnetic field. The data is normalized to its maximum for each frequency.

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P-55

Cavity optomechanics with surface acoustic waves

Ayato Okada[1], Fumikazu Oguro[1], Rekishu Yamazaki[1,2], Atsushi Noguchi[1,2], Yutaka Tabuchi[1], Koji Usami[1] and Yasunobu Nakamura[1,3]

[1]*Research Center for Advanced Science and Technology (RCAST),The University of Tokyo*

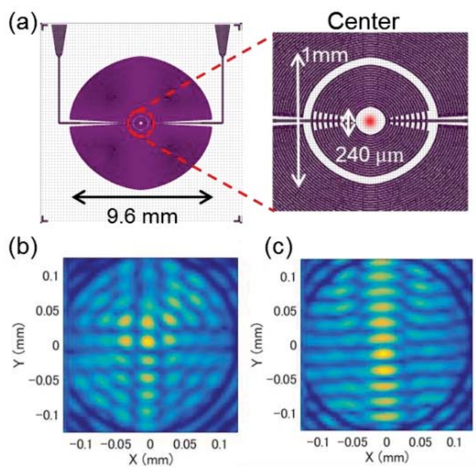
[2]*PRESTO, Japan Science and Technology Agency*

[3]*Center for Emergent Matter Science (CEMS), RIKEN*

Quantum transducer is a bidirectional coherent frequency converter between microwave and optical photons. One of the prominent candidates for such a transducer is a cavity-optomechanical system, in which a mechanical displacement modulates both microwave and optical cavities and thereby establishes coupling between microwave and optical photons. Aiming towards the goal, we are currently studying an optomechanical system using surface acoustic waves (SAWs).

The SAW is an elastic wave propagating on a surface of a solid, which can be easily excited by applying an RF voltage via an interdigital transducer (IDT) fabricated on a piezoelectric substrate. Our SAW resonator fabricated on a Y-cut $LiNbO_3$ substrate has specially designed circular IDT and Bragg mirrors (Fig. 1a) to realize SAW focusing at the center, which leads to a smaller mode volume of the SAW resonator and an improved coupling rate to the optical cavity. We optically probe this circular SAW resonator and demonstrate the SAW focusing (Fig. 1b). Owing to the tensorial nature of the photoelastic coupling between the SAW and the light, changing the polarization of the probe beam completely alters the image of the focused SAW (Fig. 1c). Next, we insert the device in an optical Fabry-Perot cavity and perform optical spectroscopy. We observe cavity-enhanced anti-Stokes scattering and demonstrate a prototype of the SAW-based optomechanical system. We experimentally evaluate the optomechanical coupling rate in the setup and find the consistence with a theoretically expected value [1].

In order to improve the coupling rate drastically, we now employ a new geometry which combines an optical waveguide fabricated on $LiNbO_3$ substrate with a conventional 1D SAW resonator. In this poster presentation, details about the new coupling scheme using the optical waveguide are also discussed.



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Quantum States and Dynamics in a Controlled Open Quantum System with Ultracold Atoms in an Optical Lattice

Takafumi Tomita,[1] Shuta Nakajima,[1] Ippei Danshita,[2] Yosuke Takasu,[1] and Yoshiro Takahashi[1]

[1]*Department of Physics, Graduate School of Science, Kyoto University, Japan*

[2]*Yukawa Institute for Theoretical Physics, Kyoto University, Japan*

Thanks to their exquisite controllability, cold-atom quantum simulators have been used for engineering various Hamiltonians of intensive theoretical interest in closed quantum many-body systems and realizing various quantum phases and transitions among those phases. In addition, several recent experiments have extended the applicability of the quantum simulators to Liouvillian dynamics of open quantum systems by introducing coupling to environment, namely, dissipation [1, 2].

We experimentally study a Bose-Hubbard system with the dissipation of the particle losses using ultracold atoms in an optical lattice [3]. In our experiment, two-body inelastic atom loss with controllable strength is implemented by introducing a single-photon photo-association (PA) process for ultracold ytterbium (^{174}Yb) atoms in a 3D optical lattice. The inelastic collision rate, which characterizes the strength of the dissipation, can be controlled by varying the intensity of the PA beam. In the dynamics subjected to a slow ramp-down of the optical lattice, we find that strong on-site dissipation favors the Mott insulating state: the melting of the Mott insulator is delayed and the growth of the phase coherence is suppressed (FIG. 1). As the strength of dissipation increases, the interference pattern becomes unclear in the shallow lattice regime. This result indicates that the growth of the phase coherence is suppressed by the strong dissipation.

The detail of the experiments and the comparison with the numerical simulation will be presented in the poster.

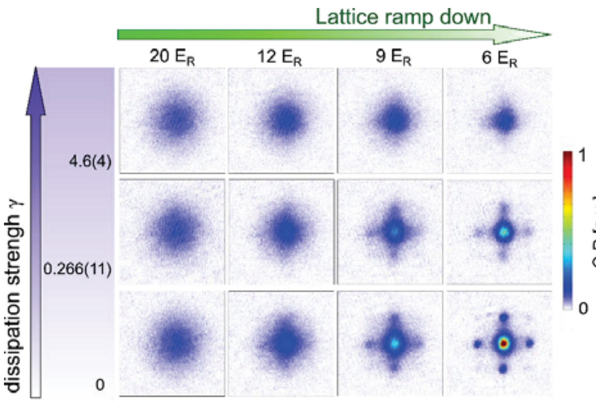

FIG. 1 Absorption image of atoms taken by Time-of-Flight method. γ is the dimensionless dissipation strength.

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Different charge and spin dynamics in a quantum dot-lead coupled system

T. Otsuka,[1,2] T. Nakajima,[1,2] M. R. Delbecq,[1,2] P. Stano,[1,3] S. Amaha,[1]
J. Yoneda,[1,2] K. Takeda,[1] G. Allison,[1] A. Noiri,[1,2] T. Ito,[1,2] D. Loss,[1,4]
A. Ludwig,[5] A. D. Wieck,[5] and S. Tarucha[1,2]

[1]*Center for Emergent Matter Science, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*

[2]*Department of Applied Physics, University of Tokyo, Bunkyo, Tokyo 113-8656, Japan*

[3]*Institute of Physics, Slovak Academy of Sciences, 845 11 Bratislava, Slovakia*

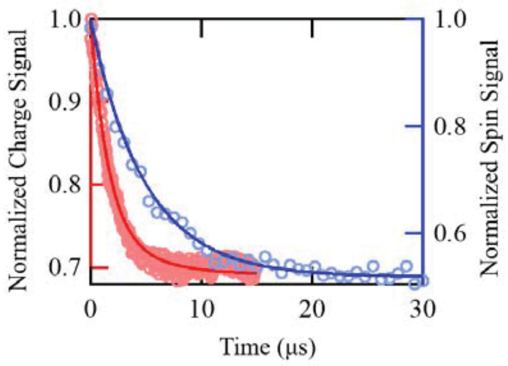
[4]*Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland*

[5]*Angewandte Festkörperphysik, Ruhr-Universität Bochum, D-44780 Bochum, Germany*

The dynamics in open quantum systems attracts keen interest in basic science and applications for quantum devices. To explore the physics of open quantum systems, semiconductor quantum dots (QDs) offer good experimental platforms. Here, we explore the charge and spin dynamics in a coupled system that consists of a single quantum dot and an open electric lead by utilizing fast high-frequency measurement techniques.

The measured device is a GaAs/AlGaAs gate-defined double QD. A target QD is coupled to an open electric reservoir through a tunneling barrier, and the charge state is monitored by a QD charge sensor. Another ancillary QD is used to detect the target spin state by utilizing Pauli spin blockade. We initialize the charge and spin states, and monitor the change of the states [1].

The figure shows one example of the observed changes of the charge and spin states as a function of the evolution time. The inner level of the target QD is set around the Fermi level of the reservoir. Both the charge and spin signals show relaxation. This is induced by the first order tunneling effect. There is a difference in the decay time between the charge and the spin states. The charge signal shows faster decay (2 μs) than the spin signal (5 μs). This difference is reproduced by a theory treating the first order tunneling process. The two solid lines in the figure show the results of the theoretical fitting. We also confirm the effect of the Fermi occupation factor in the decay time difference by changing the energy level in the QD against the Fermi level of the reservoir. These results are important in exploration and understanding of further dynamics in coupled nanosystems.



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Electron-photon interaction in silicon coupled quantum dots

Cen-Shawn Wu[a*], Chien-Han Chen[b], Chia-Yu. Hong[b] and Yu-Cheng Chang[b]

a. Department of Physics, National Changhua University of Education, Changhua, Taiwan

b. Graduate Institute of Photonics, National Changhua University of Education, Changhua, Taiwan

Coupled Quantum dots (QDs) provide an interesting playground for unraveling the rich physics that exists on a mesoscopic scale.[1] Coupled QDs, often referred to as artificial molecules, are simple intuitive extensions of single quantum dot artificial atoms with discrete energy level spectra.[2] The coupled QDs were fabricated by using electron beam lithography and reactive ion etching on a 50nm-thick top silicon layer of a Silicon-On-Insulator (SOI) wafer with a 400-nm thick buried silicon-dioxide layer (see Figure 1). Electron transport experiments on two lateral QDs coupled in series are investigated. Capacitive coupling of the two quantum dots is directly tuned electrostatically via central gate. The double dot conductance was measured as a function of the induced charge on each dot and of the inter-dot tunnel conductance to demonstrate the evolution of the charging diagram. Furthermore, we study the behavior of resonant current through the coupled QDs system under microwave photon irradiation.

Figure 2 shows measurements of current versus gate voltage of the unperturbed Coulomb peak (black curve) and the Coulomb peak behavior evolves with increasing radiation power. The asymmetric Coulomb peak in the transmission spectrum resulting from the interference between the localized and delocalized channels of the DQDs system. In addition, we observed frequency-dependent peaks related to excited states in the quantum dot. Experimental data showing the Coulomb peak polarity changes as the photon frequency is altered. While the Fano resonance has been observed in a variety of physical systems, the present system is the first convincing realization that can be tuned by photon frequency. Finally, we compare data of frequency-dependent measurements to the simulation of a model system.

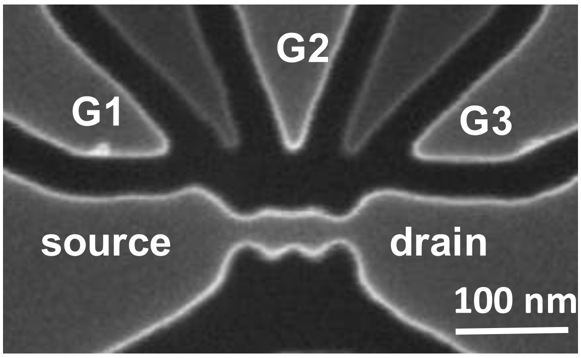

Fig.1 Image the DQDs structures with source, drain and gate electrodes.

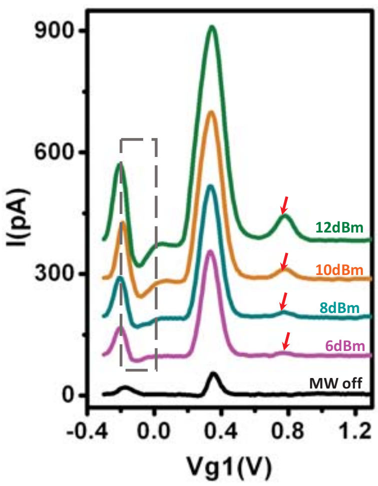

Fig.2 Current through the double dot versus gate voltage with microwave irradiation (*f*=8.3 GHz). Each curve is corresponds to the different radiation power.

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P-59

Energy control of a superconducting flux qubit with microwave irradiation

Hiraku Toida[1], Takuya Ohrai[1,2], Yuichiro Matsuzaki[1], Kosuke Kakuyanagi[1], Hiroshi Yamaguchi[1], and Shiro Saito[1,2]

1. NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi-shi, Kanagawa 243-0198, Japan

2. Department of Applied Physics, Faculty of Science, Tokyo University of Science, 6-3-1 Niijuku, Katsushika-ku, Tokyo 125-8585, Japan

E-mail: toida.hiraku@lab.ntt.co.jp

Coherence time of superconducting qubits is improved by introducing 3D architecture [1]. To control energy of a superconducting qubit, global magnetic field is usually used. However, on-chip control line is required for fast control of the energy. Introducing such a local control line to a 3D cavity is technically not trivial and may pollute clean electromagnetic environment of the cavity, which could decrease the coherence time.

Here, we demonstrate an alternative method to control the energy of a superconducting flux qubit without on-chip control line near the qubit. Our system consists of a flux qubit and a frequency tunable resonator. Tunability of the resonator is introduced by inserting a superconducting quantum interference device (SQUID) into an on-chip LC circuit where the SQUID is inductively coupled to the flux qubit. The total system is described by following Hamiltonian:

$$\hat{H} = \frac{\Delta}{2}\hat{\sigma}_x + \left(\frac{\varepsilon}{2} + g\hat{a}^\dagger\hat{a}\right)\hat{\sigma}_z + \hbar\omega\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right), \quad (1)$$

where Δ is the energy gap, ε is the flux bias, g is the coupling constant between the flux qubit and the resonator, and ω is the center frequency of the resonator. The second term contains effective magnetic field term due to the interaction between the flux qubit and the tunable resonator.

In the experiment, we measure a frequency shift of the flux qubit as a function of resonator excitation frequency for various ε. Figure 1 shows flux bias dependence of the frequency shift. As we expect from the Hamiltonian, we successfully control polarity of the frequency shift. We also confirm that the amount of the energy shift is linearly controlled by excitation microwave power, which is expected from Eq.(1).

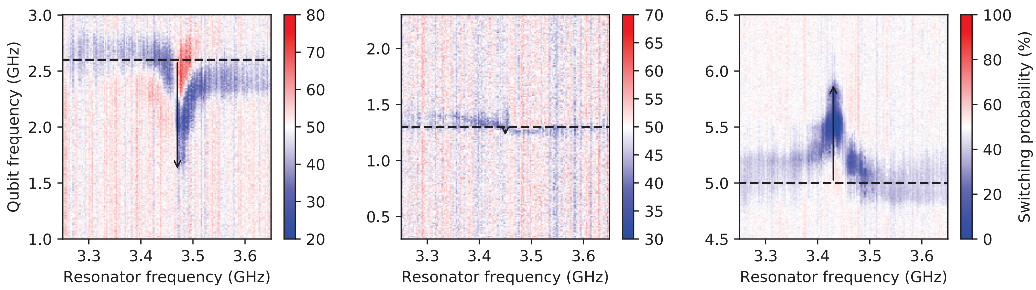

Figure 1: Qubit frequency shift as a function of excitation frequency of the resonator. Left: positive flux bias, center: zero flux bias, and right: negative flux bias.

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Quantum Memory in the Ultrastrong-Coupling Regime via Parity Symmetry Breaking

Roberto Stassi[1*] **and Franco Nori**[1,2]

[1] *CEMS, RIKEN, Saitama 351-0198, Japan*
[2] *Physics Department, The University of Michigan, Ann Arbor, Michigan 48109-1040, USA*
*E-mail: *roberto.stassi@riken.jp*

Quantum systems are affected by interactions with their environments, causing decoherence through two processes: pure dephasing and energy relaxation. It is important to prolong the coherence time of Josephson qubits and other artificial two-level atoms, but every improvement that increases the pure dephasing time is limited by energy relaxation. We show theoretically that, when these qubits are deep in the ultrastrong light-matter coupling regime and the parity symmetry is broken, it is possible to enhance their coherence time and use these qubits as quantum memories. In this regime the energy relaxation is strongly suppressed. To preserve the coherence from pure dephasing, we prove that it is possible to apply dynamical decoupling. We also use an auxiliary atomic level to store and retrieve quantum information.

Improving the quality factor of small SAW resonators by controlling the propagating velocity

A. Fujiwara[1], A. Noguchi[1, 2], A. Okada[1], R. Yamazaki[1, 2], and Y. Nakamura[1, 3]

[1]*Research Center for Advanced Science and Technology (RCAST), The University of Tokyo, Tokyo, Japan*

[2]*PRESTO, Japan Science and Technology Agency, Tokyo, Japan*

[3]*Center for Emergent Matter Science (CEMS), RIKEN, Wako, Saitama, Japan*

The hybrid quantum systems in the strong coupling regime have a potential to expand the quantum technologies. On a surface of a material, there exists a localized wave with extremely small loss, called surface acoustic wave (SAW). SAW has been coupled to various types of quantum systems such as superconducting qubits [1], quantum dots [2] and NV centers [3]. In order to enhance the cooperativity of the hybrid system, consisting of a SAW resonator and other quantum system, it is important to increase the coupling strength by reducing the mode area of the SAW resonator. One could decrease the width of Bragg mirrors and IDTs, however, the short IDT width can lead to a large diffraction loss, resulting in diminishing cooperativity. Thus, it is necessary to find a way to decrease the width of the SAW resonator, while maintaining its Q-factor high.

In this work, we measure the Q-factor of SAW resonator with an internal 'acoustic lens'. On a quartz substrate, we pattern thin-film aluminum patches, whose size is negligible compared with the wavelength of the SAW. The number of patches per unit area is the highest on the axis of the SAW resonator and gradually decreases towards the edges. The spatial pattern modulates the effective mass of the substrate and also the propagating velocity of the SAW. Using these 'lenses', we improve the Q-factor of the small SAW resonator. We discuss the change of the Q-factor with and without the lenses.

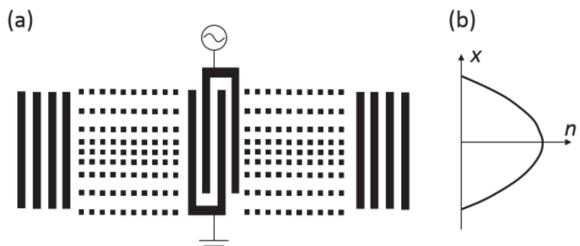

FIG. 1: Schematic of the SAW resonator with the acoustic lenses. (a) Layout of the Bragg grating mirrors, IDT and acoustic lenses. (b) Modulation of the refractive index for SAW.

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General framework for constructing near-optimal machine-learning-based decoder of the topological stabilizer codes

Amarsanaa Davaasuren[1], Yasunari Suzuki[1,2], Keisuke Fujii[3,4], Masato Koashi[1,2]

[1]*Department of Applied Physics, Graduate School of Engineering,*
The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8767 Japan
[2]*Photon Science Center, Graduate School of Engineering,*
The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8767, Japan
[3]*Department of Physics, Graduate School of Science,*
Kyoto University, Kitashirakawa Oiwake-cho, Saikyo-ku, Kyoto 606-8502, Japan
[4]*JST, PRESTO, 4-1-8 Honcho, Kawaguchi, Saitama, 332-0012, Japan*

In order to build quantum computer in a scalable manner, quantum error correction (QEC) is a vital technology to construct a few clean logical qubits from many noisy physical qubits. QEC requires fast and high-performance decoding algorithm for its implementation. Since there is no efficient and optimal decoding algorithm for QEC in general, various deterministic decoding algorithms have been proposed. However, they sacrifice either of accuracy, efficiency, or applicability to various noise model.

Using machine learning as a part of decoding algorithm is one of the most promising solutions to this problem. Once we can appropriately train a chosen prediction model with a given noise model, it is expected that the trained model can efficiently predict near-optimal decoding methods with a high probability. Therefore, several machine-learning-based decoders have been proposed recently. However, they only mapped the decoding problem to the task of machine learning, and it has not been discussed what a part of decoding algorithm should be delegated to machine learning.

In order to clarify this, we introduced a general framework of machine-learning-based decoders, linear prediction framework, which can treat all the existing machine-learning-based decoders as specific cases. With this framework, we analytically derived the conditions for guaranteeing that the whole decoding algorithm becomes optimal when the prediction model is correctly trained. We also proposed a criterion, normalized sensitivity, for achieving high performance. We numerically confirmed that the performance of the machine-learning-based decoder constructed with this guiding principle is superior to those of the existing machine-learning-based decoders. We also confirmed that the performance of the proposed decoder is close to the optimal one in the both surface codes and color codes.

A 3D JPA

Imran Mahboob[1†], Hiraku Toida[1], Kosuke Kakuyanagi[1], Yasunobu Nakamura[2] and Shiro Saito[1]
[1]*NTT Basic Research Laboratories, NTT Corporation, Atsugi-shi, Kanagawa, Japan*
[2]*RCAST, The University of Tokyo, CEMS RIKEN, Japan*
[†]imran.mahboob@lab.ntt.co.jp

Josephson parametric amplifiers (JPAs) pioneered decades ago [1] have re-emerged as essential components for quantum non-demolition readout of superconducting qubits. The Josephson junction at the heart of the JPA is invariably embedded in a waveguide resonator in the guise of superconducting quantum interference device (SQUID). The JPA can then be activated in a four-wave/three-wave mixing configuration by pumping current/flux at the natural/twice the natural frequency of the resonator to non-linearly modulate the Josephson inductance [2, 3].

Meanwhile 3D cavities have emerged as clean electromagnetic environments thus leading to ultra-high quality factor resonators which offer a superior circuit QED architecture and it has resulted in qubits with unprecedented lifetimes and coherence [4, 5]. Here we extend this platform to build a 3D JPA namely a high quality factor 3D resonator embedded with a flux pumped SQUID. This architecture offers reduced participation from the SQUID inductance thus leading to a dilution in the Josephson non-linearity which whilst reducing the frequency tunability of the 3D JPA results in an enhanced dynamic range. Indeed experimentally we observe gains exceeding 40 dB with a dynamic range approaching 6 orders of magnitude, a 1dB compression point at -103 dB with a 38 dB gain and the ability to amplify signals of $\lesssim$0.005 photons in a 4 MHz bandwidth with less than 1 quanta of added noise at 8.1 GHz. In addition to offering amplification with unprecedented fidelity this architecture also lays the foundations to study side-band quantum optics with microwave photons [6].

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This work was supported by CREST, JST.

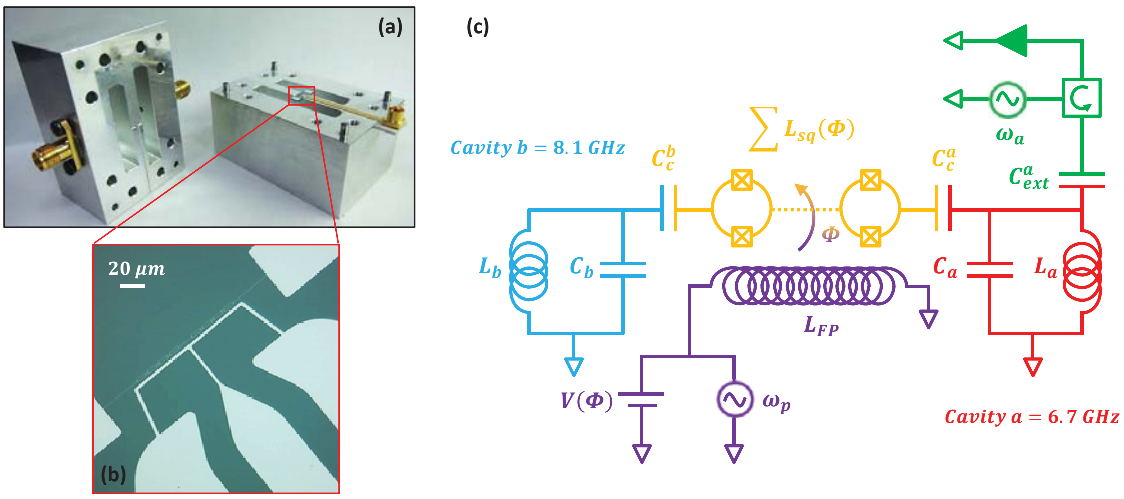


Figure 1: (a) A photograph showing two 3D cavities embedded with SQUIDs that are capacitively coupled to the cavities via large rectangular antennae and flux pumped via a coplanar waveguide on a ceramic substrate. (b) An optical image showing an array of 8 Al/AlO_2 SQUIDs, patterned via e-beam on a highly resistive silicon substrate, which are galvanically connected to the antennae and inductively coupled to the flux pump line. (c) A simplified circuit schematic depicting the 3D cavities capacitively coupled to the array of flux pumped SQUIDs where one of the cavities is probed.

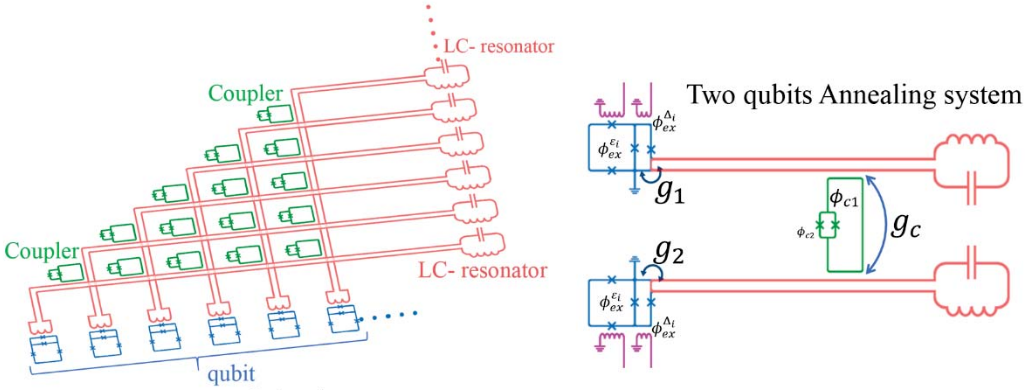
Superconducting Qubits Coupling via Lamped Element Resonators toward Quantum Annealing

A.Tomonaga [A], H. Mukai [A], Y. Zhou [A], J.S. Tsai [AB]

[A]*Dept. of Phys, Tokyo Univ. of Science.* [B]*Center for Emergent Matter Science, RIKEN*

We propose a new type of a quantum circuit for a quantum annealing system. This circuit can achieve the full interaction spin system using lumped element resonators for qubit couplings. The increasing interaction is definitely necessary for mapping practical optimization problem. This circuit could control all parameters needed for annealing. Using rf-SQUID couplers, ferromagnetic and antiferromagnetic couplings could be achieved.

As the first experiment, the lumped element resonators with a long edge coupled line successfully invented. As shown in current distribution(Fig.2), the lumped element resonator does not need to consider its waveform when qubits couple to each other. It is possible to couple many qubits within a small space. In the poster, we will show how achieve the full coupling quantum annealing system using artificial atoms, and some experimental data about components of the machine.



$$H_{\text{optimization}} = \sum_i \frac{\Delta_i\left(\phi_{ex}^{\Delta_i}(t)\right)}{2}\sigma_i^z + \sum_{i,j}\frac{4g_i g_j g_{c_{ij}}}{\omega_i\omega_j-(2g_{c_{ij}}^2)}\sigma_i^z\sigma_j^z \qquad H_{\text{Fluctuation}} = \sum_{i=1,2}\frac{\varepsilon_i\left(\phi_{ex}^{\varepsilon_i}(t)\right)}{2}\sigma_x^i$$

Fig.1. Annealing Hamiltonian of the full coupling annealing circuit.

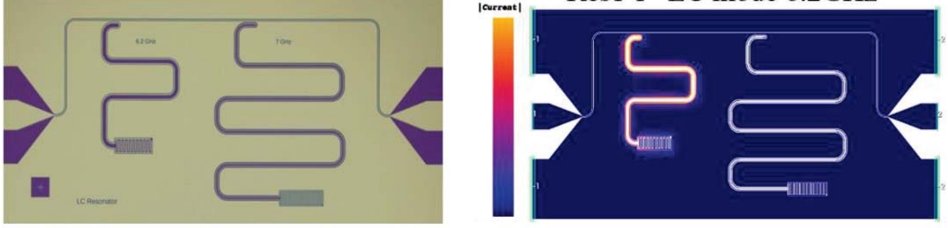


Fig.2. The lumped element resonator's Micrograph and current distribution of EM simulation

Dynamics of an open quantum system based on gated GaAs quantum dots

Sen Li[1], T. Otsuka[1,2], G. Allison[1], A. Noiri[1,2], J. Yoneda[1,2], K. Takeda[1,2], T. Nakajima[1,2], A. Ludwig[3], A. D. Wieck[3], and S. Tarucha[1,2]

[1] *Center for Emergent Matter Science, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*

[2] *Department of Applied Physics, University of Tokyo, Bunkyo-ku, Tokyo 113-8656, Japan*

[3] *Lehrstuhl fürAngewandte Festkörperphysik, Ruhr-Universität Bochum, D-44780 Bochum, Germany*

Quantum simulation offers a promising method to search for solutions to complex quantum mechanical problems, which are intractable on classical quantum computers. Among these problems, dynamics of a quantum many body system in the non-equilibrium regime is of interest and fundamental importance. Semiconductor quantum dots (QDs) could well confine electrons with charge and spin degrees of freedom, from which quantum many body interaction can arise. More importantly, the physical parameters in such QDs systems usually can be readily engineered and the manipulation techniques of the electrons in QDs have been developed and established. Here we investigate the spin dynamics of an open quantum system which consists of a double-QD coupled to an electronic reservoir. We observe fast spin relaxations in the target QD with sudden enhancement of the coupling to reservoir by pulsing the barrier gate. With comparison of results at different pulse amplitude, we confirm that this fast dynamics originates from the 2nd order co-tunneling process. The ideas of our approach may be used to investigate more complex many-body physics using quantum dots.

Quantum-state swapping between a superconducting qubit and a propagating microwave photon

Zhi-Rong Lin[1], Kunihiro Inomata[1,2,3], Kazuki Koshino[4], Shumpei Masuda[4], Tsuyoshi Yamamoto[1,5], and Yasunobu Nakamura[1,6]

[1]*Center for Emergent Matter Science, RIKEN, Japan*

[2]*National Institute of Advanced Industrial Science and Technology, Japan*

[3]*PRESTO, Japan Science and Technology Agency (JST), Japan*

[4]*College of Liberal Arts and Sciences, Tokyo Medical and Dental University, Japan*

[5]*IoT Devices Research Laboratories, NEC Corporation, Japan*

[6]*Research Center for Advanced Science and Technology, The University of Tokyo, Japan*

In one-dimensional (1D) optical/microwave setups, a propagating electromagnetic field is confined in a 1D mode and the light-matter interaction can be drastically enhanced by the interference between the incident field and scattered field by quantum emitters. As a result, we can achieve various unique optical phenomena in 1D optical setups. For example, when a semi-infinite 1D field interacts with an impedance-matched Λ system, a Raman transition is deterministically induced in the Λ system by a single photon.

Recently, we have proposed and realized an impedance-matched Λ system by the dressed-state engineering of a qubit-resonator system [1, 2]. The proposed device enables deterministic down-conversion of incident microwave photons with efficiency ~75% [2] and single microwave photon detection with efficiency ~66% [3]. Here we present an experimental observation of the deterministic and bidirectional quantum-state transfer between a superconducting flux qubit and a propagating microwave photon, in which the photon qubit is encoded on its carrier frequencies. This realizes a qubit-photon SWAP gate, which enables the two-qubit gate operations between remote superconducting qubits.

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Time-domain measurements of a qubit-harmonic oscillator circuit in the ultra-strong coupling regime

T. Fuse[1], F. Yoshihara[1], S. Ashhab[2], K. Kakuyanagi[3],
S. Saito[3], and K. Semba[1]

[1]*Advancec ICT Institute, National Institute of Information and Communications Technology,*

[2]*Qatar Environemnt and Energy Research Institute, Hamad Bin Khalifa University, Qatar Foundation,*

[3]*NTT Basic Research Laboratories, NTT Corporation*

The fields of cavity- and circuit-quantum electrodynamics (cavity- and circuit-QED) have been extensively studied in the past decades. Especially, so-called strong coupling between an (artificial) atom and a photon, where the coupling rate is larger than the decoherence rates, is a basis of many quantum technologies. Usually, the coupling energy ($\hbar g$) is much smaller than the atomic and the photon energies ($\hbar\Delta$ and $\hbar\omega$). When the coupling energy becomes as large as ~10 % of a photon energy ($g/\omega \sim 0.1$, ultra-strong coupling regime), a finite number of photons is expected in the ground state of the coupled system. When the coupling energy is even larger ($g/\omega \sim 1$, deep-strong coupling regime), even more interesting properties, such as highly entangled ground states, are predicted [1]. In circuit-QED setups, so far, only the transition energy spectra of such circuits have been demonstrated [2-4]. To further characterize the ultra-strongly and deep-strongly coupled systems, time-domain measurements are required.

In this study, we have driven a flux qubit – LC harmonic oscillator circuit in the ultra-strong coupling regime, and measured its response in the time-domain. The Rabi oscillations are shown in the Fig. 1. In the presentation, the measured data of the relaxation time and free-induction decay time will be shown and discussed.

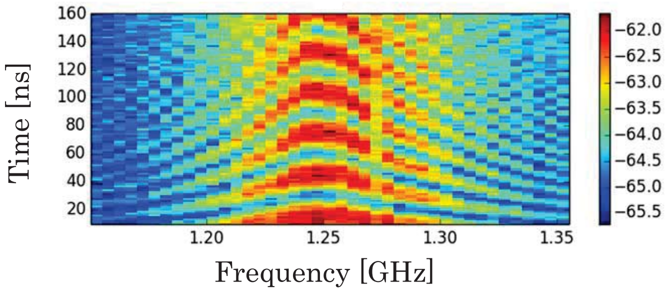

Figure 1. Rabi oscillations between the lowest two energy states of the coupled circuit at the symmetric point.

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Towards quantum simulation of frustrated spin systems with single-site-resolved imaging

Ryuta Yamamoto, Ippei Nakamura, and Takeshi Fukuhara
RIKEN Center for Emergent Matter Science (CEMS)
Quantum Many-Body Dynamics Research Unit

Ultracold atoms in optical lattices offer a useful platform for studying condensed matter physics because this provides us many controllable parameters and clean systems. Using the lattice tunability, geometrically frustrated lattices such as triangular and kagome lattices can be realized. These lattice systems enable us to study quantum many-body physics with spin frustration [1], in which many unique physical phenomena such as spin ice and spin liquid will occur. In recent studies, single-site-resolved imaging technique, so-called quantum gas microscope, has been realized in a two-dimensional square optical lattice [2]. This technique allows us to directly observe the in-trap atom distribution and to track quantum dynamics with single-site resolution [3]. Applying a quantum gas microscope to geometrically frustrated lattice systems will open up new possibilities for quantum simulation and quantum many-body dynamics. For example, we may observe quench dynamics of spin frustration with single-site resolution. To this end, we are developing a triangular optical lattice system with single-site-resolved imaging. We construct a triangular optical lattice, and load a Bose-Einstein condensate of rubidium-87 atoms into the triangular lattice (Figure 1). In this presentation, we report our latest experimental results.

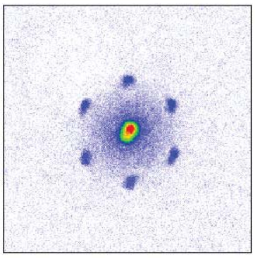

Figure 1. Momentum distribution of Bose-Einstein condensate in a triangular optical lattice by time-of-flight (TOF) measurement. TOF time is 25 milliseconds.

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Study on Scalable One-way Quantum Computation in Circuit QED

K. Sakata[1,†], S. Takahashi[1], N. Sugihara[1], Y. Nakajima[1], J.S. Tsai[1,2]
[1]*Dept. of Phys., Tokyo Univ. of Science.* [2]*Center for Emergent Matter Science, RIKEN.*
†*keiichi.sakata@riken.jp*

Quantum computers are the machines that use the quantum mechanical effects. These are considered to be effective against several problems, which are difficult to calculate with conventional supercomputers, such as prime factorization and combinatorial optimization. In order to solve the real problems, fault-tolerance and scalability are necessary for quantum computers. However, the current quantum computers realized in the most advanced circuit QED have only about tens of bits.

We aim to realize a fault-tolerant and scalable quantum computer by using one-way quantum computation which is different from conventional method in circuit QED. In this poster session, we will explain theoretical and experimental research toward realization of quantum computers based on this new method.

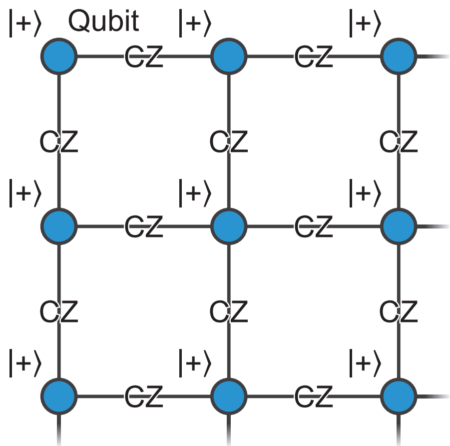

Figure 1: 2D cluster state.

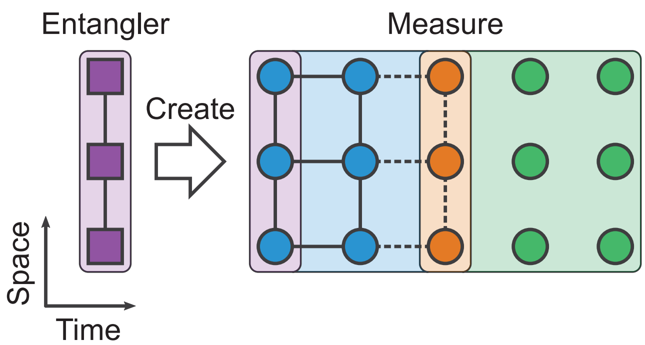

Figure 2: Time domain cluster state.

Mapping the magnetostatic mode structures of a ferromagnetic sphere

A. Gloppe[1], A. Osada[1], R. Hisatomi[1], Y. Nakata[1], Y. Nakamura[1,2], K. Usami[1]
[1]*Research Center for Advanced Science and Technology (RCAST), The University of Tokyo*
[2]*Center for Emergent Matter Science (CEMS), RIKEN*
arnaud.gloppe@qc.rcast.u-tokyo.ac.jp

The exploration of the interaction of light with spin waves in ferromagnets within an optical cavity opens a new class of chiral photonic devices and constitutes a necessary stepping stone towards the coherent optical manipulation of magnons in the quantum regime [1]. The developments made so far in cavity optomagnonics have been focused on the fundamental magnetostatic mode of an yttrium iron garnet (YIG) sphere, so-called "Kittel mode" [2,3] and led to the observation of a magnon-induced Brillouin scattering between optical whispering gallery modes. Very recently, higher-order magnetostatic modes played a central role in demonstrating the exchange of orbital angular momenta between magnon and photons during Brillouin scattering processes [4]. With a reduced mode volume and a more elaborate spin texture, they could couple more efficiently with the optical whispering gallery modes hosted by the YIG sphere, lying in the vicinity of the sphere surface equatorial plane. Though the resonance frequencies of these modes could be coarsely predicted theoretically in the magnetostatic approximation [5], deviations due to the actual sample properties or environment, as well as possible hybridization of the modes, could cause strong misinterpretations. Hence, unambiguously experimentally identifying higher-order magnetostatic modes in a sphere is required to properly scrutinize their interaction with light.

We demonstrate a scheme to map the magnetostatic mode structures of a ferromagnetic sphere. Using two small loop coils in close proximity with a millimetric YIG sphere, we perform microwave transmission measurements at various altitude-longitude coordinates. These signals are found to be very sensitive to the magnon mode structures (Fig. 1), making possible their identification and the systematic investigation of the opto-magnonic coupling in cavity.

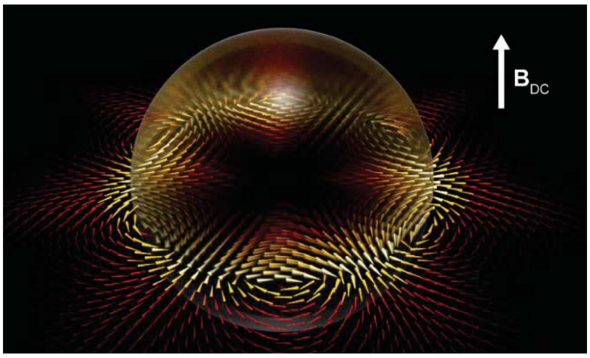

Fig. 1 Magnetic field induced by the magnetostatic *330* in the equatorial plane.

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P-71

Topological pumping in strongly interacting bosons and fermions

Masaya Nakagawa[1], Shunsuke Furukawa[2],
Tsuneya Yoshida[3], Robert Peters[3], and Norio Kawakami[3]
[1]*RIKEN Center for Emergent Matter Science (CEMS)*
[2]*Department of Physics, University of Tokyo*
[3]*Department of Physics, Kyoto University*

Adiabatic quantum dynamics sometimes causes nontrivial effects which cannot be found in its instantaneous ground state. In 1983, Thouless [1] proposed that an adiabatic cycle of one-dimensional band insulators induces quantized charge pumping, which is called ``topological pumping”, due to the topological nature of the ground-state wavefunctions. After almost 30 years from the original proposal by Thouless, the topological pumping was finally observed using ultracold atoms in optical lattices [2, 3]. Since the interactions between ultracold atoms are highly controllable, it is a natural and fascinating direction to study correlation effect on topological pumping and to search for novel interaction-induced pumping. In this presentation, we study topological pumping in strongly correlated systems of bosons and fermions from a viewpoint of symmetry-protected topological (SPT) phases. First, we show that a quasi-one-dimensional limit of various quantum Hall states gives a systematic construction of interaction-induced topological pumping, which includes fractional charge pumping and intriguing ``off-diagonal” topological pumping [4]. Second, we show that correlation effects on the Thouless pumping can be naturally understood as a crossover from fermionic to bosonic SPT phases [5]. We demonstrate that the topological pumping in the correlated Rice-Mele model breaks down with strong interactions based on this mechanism.

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Simulating 1-d classical XY model using a non-degenerate optical parametric oscillator network

Yutaka Takeda[1,2,3], Shuhei Tamate[4], Yoshihisa Yamamoto[5,6], Hiroki Takesue[3], Takahiro Inagaki[3], Shoko Utsunomiya[1,2]

[1]*Department of Physics, Faculty of Science, Tokyo University of Science*
[2] *National Institute of Informatics*
[3] *NTT Basic Research Laboratories, NTT Corporation*
[4]*Research Center for Advanced Science and Technology (RCAST), The University of Tokyo*
[5] *ImPACT Program, Japan Science and Technology Agency*
[6] *E. L. Ginzton Laboratory, Stanford University*
E-mail: 1216623@ed.tus.ac.jp

We present an experimental implementation of a classical XY model using a non-degenerate optical parametric oscillator (NOPO) network. Our goal is realizing artificial XY spins using optical resonators and simulating an XY model in thermal equilibrium.

A classical XY spin is expressed by an optical phase of an NOPO in our scheme. A large number of NOPOs are generated by time-division-multiplexing in a single fiber ring resonator. We formed an NOPO network by mutual injections between NOPOs, which is implemented by optical delay lines. The Gibbs-Boltzmann distribution of an implemented XY model is realized as a steady state distribution of the phases of the network. The effective temperature can be controlled by external experimental parameters.

As a proof-of-principle experiment, we implemented a one-dimensional ferromagnetic XY model, which is the simplest configuration in our scheme. We demonstrated sampling of the artificial XY model at different temperature settings and evaluated temperature controllability in terms of relative phase distributions between two adjacent spins and mean energies. The experimental results show that we can control the effective temperature and agree with numerical simulations of implemented phase dynamics.

[1] Y Takeda *et al* 2018 *Quantum Sci. Technol.* **3** 014004

Demonstration of a two-qubit device in a coaxial circuit QED architecture

T. Tsunoda, J. Rahamim, A. Patterson, P. Spring, M. Esposito, G. Tancredi, and P. J. Leek

Clarendon Laboratory, Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom

E-mail: takahiro.tsunoda@physics.ox.ac.uk

The development of superconducting circuits during the last two decades has been remarkable. Coherence times and quantum logic gate fidelities now reproducibly reach levels high enough in principle to enable large scale fault-tolerant circuits.

An important current focus is the design of circuit architectures that can be easily scaled to many qubits, without compromising on coherence and control capability. In this direction, we have developed a coaxial circuit QED architecture in which qubit and resonator are fabricated on opposing sides of a single chip, and control and readout wiring are provided by coaxial wiring running perpendicular to the chip plane making the architecture potentially scalable to arrays of many qubits with little or no redesign [1].

Here we present measurements of two-qubit devices in this architecture, in which we use static frequency single-Josephson-junction coaxial transmon qubits and weak direct capacitive coupling, so as to implement a cross resonance interaction [2]. We present, an analysis of the basic properties of the devices, including coherence, readout and control selectivities, and single and two-qubit gate fidelities.

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Magneto-spectroscopy of a spin-qubit in cavity

M.C. Dartiailh, J.J. Viennot, A. Cottet, T. Kontos

1. Laboratoire Pierre Aigrain, Ecole Normale Suprieure-PSL Research University, CNRS, Universit Pierre et Marie Curie-Sorbonne Universits, Universit Paris Diderot-Sorbonne Paris Cit, 24 rue Lhomond, 75231 Paris Cedex 05, France 2. JILA and Department of Physics, University of Colorado, Boulder, Colorado, 80309, USA
E-mail: matthieu.dartiailh@lpa.ens.fr

Electron spins and photons are complementary quantum mechanical objects which can be used to carry, manipulate and transform quantum information. Combining them into a scalable architecture is an outstanding challenge, as the natural coupling of the spin to the magnetic part of the electromagnetic field is very weak. In order to coherently couple a single spin to photons one has to build an artificial interface enhancing the spin/photon coupling while preserving the spin coherence. Spin/photon interfaces have generated a lot of interest in the optical domain. However, the use of a circuit design in the microwave range is particularly appealing due to the versatility and the scalability offered by nanofabrication techniques.

Using a circuit design based on a nanoscale spin-valve , we engineer a strong artificial spin orbit coupling in carbon nanotube based double quantum dot. This artificial spin orbit coupling coherently hybridize the individual spin and charge states of the double quantum dot while preserving the spin coherence [1,2]. This scheme allows us to increase by five orders of magnitude the natural (magnetic) spin-photon coupling, up to the MHz range at the single spin level. Our coupling strength yields a cooperativity which reaches 2.3, with a spin coherence time of about 60ns [2].

Furthermore, the cavity allows to probe the dispersion of the device levels, which have a finite coupling to light, both with respect to the gate voltage and the magnetic field. Using these tools, we identify qualitative differences of the spectrum depending on the parity of the double quantum dot occupation, and show that the magnetic properties of our system can change with its electrostatic environment. Gaining a finer control on those properties may be key in reaching the strong coupling regime and later on performing non-destructive spin read-out and distant spin coupling.

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