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Science Research Grants from the Ministry of
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Research on Innovative Areas
(Proposal-Based Research)

Project manager : Jaw-Shen Tsai, RIKEN

QUANTUM CYBERNETICS

Quantum cybernetics

Interdisciplinary research on quantum control and its application to quantum computation

http://www.riken.jp/Qcybernetics/index.html

QUANTUM
CYBERNETICS

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Research Areas

Research topic: Solid-state device quantum cybernetics
Proposed research A01: Study of superconducting quantum cybernetics

Project Leader: Jaw-Shen Tsai (Team Leader, RIKEN; Senior Researcher,
NEC Nanoelectronics Laboratory)

1. Subgap leak current in superconducting tunnel junction explained

The current-voltage characteristics of superconducting tunnel junctions should reflect the BCS density of states, so that within the voltage that corresponding to the superconducting energy gap, the current is greatly suppressed. However, in the real superconducting tunnel junctions, leakage currents considerably larger than that expected from the BCS density of states are always observed. The excess leakage current signifies the existence of unwanted quasiparticles, and it would act as source of decoherence of qubits. Even in classical devices, subgap leakage results with hindered performances in superconducting digital circuits as well as quantum current standards. As for the origin of the leakage current, it remained largely as a mystery for some time. We have carried out two different sets of experiments and obtained new insights to the old problem. The importance of the environmental photon assisted tunneling [1] and intrinsic interface states [2] as the sources of the subgap leakage current were established.

The subgap leakage in superconductor/insulator/normal-metal (S/I/N) junction is a serious problem for the quantum current standard. We have shown the leakage current can originate from the influence of the electromagnetic environment of a tunnel junction. We were able to reduce the leakage of an NIS junction by an order of magnitude by local capacitive filtering.

In another set of experiments using superconductor/insulator/superconductor (S/I/S) junctions, by tunneling spectroscopy we observe a characteristic subgap feature, and attribute it to the existence of inherent quasiparticle states at the interface between the superconductor and tunnel barrier oxide. The interface quasiparticle density of states is directly evaluated. Our findings suggest that a careful choice of the superconducting electrode and the tunnel barrier materials together with appropriate methods in producing junction interfaces is important in order to improve the performance of superconducting tunnel junction circuits. The above mentioned environmental assisted tunneling is very much suppressed in the S/I/S configulation.

[1] J. P. Pekola, V. F. Maisi, S. Kafanov, N. Chekurov, A. Kemppinen, Yu.A. Pashkin, O.-P. Saira, M. Mottonen, and J. S. Tsai ***"Environment-assisted tunneling as an origin of the Dynes density of states"***, Physical Review Letters, 105, 026803, 2010
[2] Not published

2. Photons interacting with superconducting qubits acting as tunable mirrors

Superconducting circuits can act as tunable mirrors [1-5]. Thus, these can be used for various types of interferometry, including: Landau-Zener-Stuckelberg [1], Breit-Wigner-Fano [2,3], and Fabry-Perot interferometry [4,5].

These devices can be implemented using quasi-one-dimensional open systems where photons are injected from the left and move towards the right side of the device. Along the way, the photons interact with either one [2,3] or two [3,4] superconducting qubits, or detuned resonators, acting as two-level artificial atoms, controlled by changing the applied electric and/or magnetic fields on the qubits. These artificial atoms, working as tunable mirrors, can change the reflection and transmission coefficients of the photons confined in waveguides.

Let us first consider the case of a single two-level artificial atom coupled to photon moving inside a waveguide [2,3], see Fig. 1(a). When the energy of the incoming photon matches the energy spacing of the artificial atom, the photon is reflected, otherwise it is transmitted. This type of single-photon switch exhibits Breit-Wigner scattering: now in one dimension instead of the standard three dimensional case for natural atoms. This scattering produces a symmetric Lorentzian peak in the reflection coefficient, versus frequency, of the photon. This situation occurs when the dispersion relation of the incoming photon is linear, as in a transmission line resonator, acting as a "rail" guiding the motion of the photons [2].

When the photon dispersion relation is nonlinear [2], for long-wavelength photons propagating in a quasi-one-dimensional array of coupled cavities, the reflection coefficient exhibits a more interesting asymmetric Fano line shape, due to the interference between the continuous mode of the incoming photon and the discrete energy levels of the qubit. Thus, for single-photon transport in a one-dimensional waveguide, the photons can be partially or totally reflected by a controllable two-level artificial atom which can act as a tunable mirror [2,3].

The Fabry-Perot interferometer, which consists of two highly reflecting planar mirrors, provides the simplest cavity. It is then natural to ask the question: "is it possible to construct a quantum version of a Fabry-Perot interferometer?" Namely, to build a one-dimensional waveguide, with two tunable-mirrors made of quantum scatterers [4,5], see Fig.1 (b). Ref. [4,5] focused on this question and studied quantum analogs of the Fabry-Perot interferometer. It was found [4,5] that two separate tunable two-level systems, or resonators, interacting with photons in a waveguide can also create, between them, single-photon quasi-bound states. In some regimes, the photons can be localized around the scatterers, which can act as impurities, producing isolated states in the gap of the energy spectrum.

[1] S. N. Shevchenko, S. Ashhab, F. Nori, *Landau-Zener-Stuckelberg interferometry*, Phys. Reports **492**, 1 (2010).

[2] L. Zhou, Z.R. Gong, Y.X. Liu, C.P. Sun, F. Nori, *Controllable scattering of photons inside a one-dimensional resonator waveguide,* Phys. Rev. Lett. **101**, 100501 (2008).

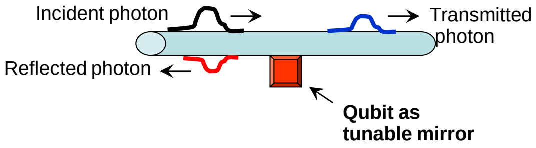
[3] L. Zhou, S. Yang, Y.X. Liu, C.P. Sun, F. Nori, *Quantum Zeno switch for single-photon coherent transport,* Phys. Rev. A **80**, 062109 (2009).

[4] L. Zhou, H. Dong, Y.X. Liu, C.P. Sun, F. Nori, *Quantum super-cavity with atomic mirrors*, Phys. Rev. A **78**, 063827 (2008).

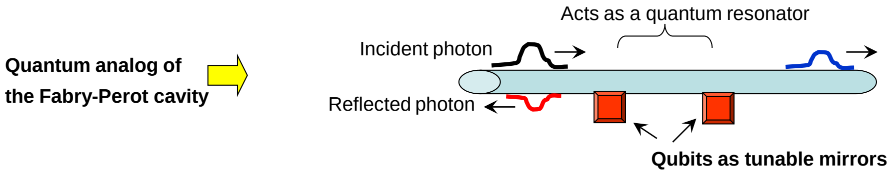
[5] J.Q. Liao, Z.R. Gong, L. Zhou, Y.X. Liu, C.P. Sun, F. Nori, *Controlling the transport of single photons by tuning the frequency of either one or two cavities in an array of coupled cavities*, Phys. Rev. A **81**, 042304 (2010).

Figure caption: Schematic diagram of a waveguide acting as a “rail” for photons, interacting with either one (a) or two (b) scatterers (either qubits or detuned resonators) acting as “tunable mirrors”.

(a) Controllable scattering of photons in a 1D waveguide coupled to a qubit: a single-photon switch.



(b) Photon in the waveguide interacting with two tunable scatterers



Proposed research A02: Study of the control, measurement, and transfer of quantum information using a semiconductor nanoassembly

Project Leader: Yasuhiro Tokura (Executive Manager, NTT Basic Research Laboratories)

I. **Large anisotropy of spin-orbit interaction** It is known that the spin-orbit interaction (SOI) in the semiconductor materials is highly controllable and is one of the important ingredients for the efficient control of the electron spins by the electric field. We have observed large anisotropy of SOI as a function of applied magnetic field direction by inspecting excitation spectra of a two-terminal current through an In As quantum dot (QD). Figures (a) to (d) show the magnetic field dependences of the energies of the ground and the first excited states for various in-plane direction, ϕ, of the field. (Fig. (e)) The spin state of the ground state and that of the first excited state direct oppositely. As can be seen in the region pointed by the arrows, the two energies approach and eventually "anti-cross". The spacing of this anti-cross characterizes the strength of SOI, which is plotted in Fig. (f) with theoretical solid curve. At ϕ=60 degree, the size of SOI anti-crossing completely vanishes. This work had demonstrated an accurate method to determine the strength of SOI and had shown that its strength can be controlled. [1] In future, we will try to control SOI by other external methods, like gate voltages, *etc.*

II. **g-factor controlled double quantum dot** Semiconductor coupled QD system is the main arena for coherent manipulation and read-out of electron spin qubits. We had fabricated GaAs-based vertical series double QD system, where one of the QDs contains 4% of In. By measuring transport properties under an external magnetic field, we had confirmed that the electrons in the two QDs have different Lande g-factors (0.33, 0.89). In a series coupled QD system with different g-factors, the resonant tunneling condition can be satisfied only for the electron with one spin direction under a magnetic field. Interestingly, even under this resonant tunneling condition, we had observed strong suppression of the current, which can be explained by the Coulombic suppression by the non-resonant spin trapped and localized in the QD system: "spin bottleneck effect". [2] This effect enables accurate estimation of the g-factors or g-tensors[3] and, realizes intriguing quantization of the transient current. [4]

[1] S. Takahashi, R. S. Deacon, K. Yoshida, A. Oiwa, K. Shibata, K. Hirakawa, Y. Tokura and S. Tarucha, Phys. Rev. Lett. 104, 246801 (2010).

[2] S. M. Huang, Y. Tokura, H. Akimoto, K. Kono, J. J. Lin, S. Tarucha and K. Ono, Phys. Rev. Lett. 104, 136801 (2010).

[3] Y. Tokura, T. Kubo, Y. -S. Shin, K. Ono, and S. Tarucha, Physica E 42, 994-998 (2010).

[4] Yasuhiro Tokura, Keiji Ono, and Seigo Tarucha, J. Phys.: Conf. Ser. 193 (2009) 012102.

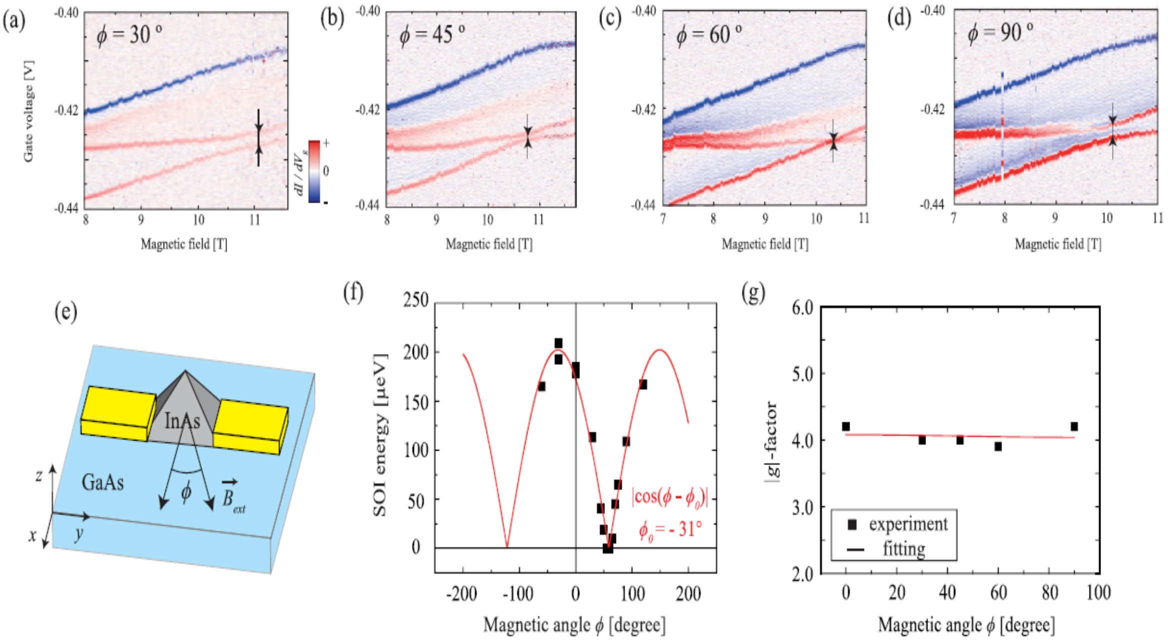


Fig. (a)-(d) Magnetic field dependences of excitation spectra of the current through InAs QD for various azimuthal angle of the field ϕ. The regions indicated by the arrows are the anti-crossing between the ground state (spin-down) and the excited state (spin-up). (e) The schematics of the device and the angle of the field. (f) Azimuthal dependence of the size of anti-crossings (g) Azimuthal dependence of the Lande

Research topic: Molecular spin quantum cybernetics

Proposed research B01: Molecular spin quantum control

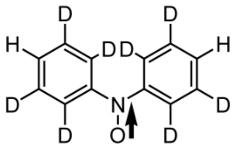
Project Leader: Masahiro Kitagawa (Professor, Graduate School of Engineering
Science, Osaka University)

Acceleration of dynamic nuclear polarization with photo-excited triplet electrons by deuteron decoupling

We have been using deuterated host crystal to reduce the number of proton spins and shorten the period to achieve dynamic nuclear polarization (DNP) with photo-excited triplet electrons in pentacene molecules. We have found and recently demonstrated that the DNP can be further accelerated by decoupling deuterons with continuous wave irradiation as a result of increased spin diffusion rate among protons. The result has potential applications in initialization of nuclear spin qubits and quantum memories or supplying fresh qubits for quantum error corrections.

Implementation and Visualization of the Occurrence of Electron-Spin Bus Based Tripartite Entanglements in Molecular Spins

Molecular spins are the latest arrival among candidates for matter spin qubits, but have drawn attention to not only the scalability issue of qubits but also mixture of matter spin qubits with intrinsically different nature of spins. In view of any implementation of molecular spin quantum cybernetics, the identification and characterization of electron-spin bus based entanglements are a key issue among the diverse topics in the field of QC/QIP. Additionally, molecular spins enjoy significant advantages in terms of qubit designs and control of electron-spin g-tensors (g-tensor engineering). During the last six months, we have established the identification/characterization of tripartite entanglements between an electron-spin qubit and two inequivalent proton client qubits in isotope-labeled diphenylnitroxide **1** diluted in the diamagnetic host lattice **2** at any desired concentration. The occurrence of the entanglements has been proven by invoking a Time-Proportional-Phase-Increment (TPPI) method in pulse-based electron-nuclear-mutiple-resonance spectroscopy. The TPPI method allows us to measure the phase control relevant to the spin qubits involved in the entanglements. We have also achieved the visualization of the occurrence of the bi-/tripartite entanglements in molecular spins by using rectangular parallelepipeds to differentiate between the entanglements in the bus systems.



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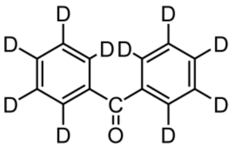

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Research topic: Atomic and ionic system quantum cybernetics

Proposed research C01: Quantum control using cold atoms

Project Leader: Yoshiro Takahashi (Professor, Atomic Physics, Kyoto University
Graduate School of Science)

In this proposed research, we aim at achieving coherent quantum control with cold atoms such as a realization of quantum computer and quantum simulator using ultra-cold atoms in an optical lattice, quantum metrology, and quantum feedback using a nuclear spin ensemble.

In the effort towards realization of optical lattice quantum computer, we successfully load the Bose-Einstein condensate (BEC) created in a thin glass cell region into a 1D optical lattice, and apply a large magnetic field gradient along the optical lattice axis. From the excitation spectrum obtained using the magnetic-sensitive ultra-narrow optical transition, we successfully reproduce the spatial distribution of the BEC. We also performed quantum simulation of strongly correlated Bose-Fermi mixed quantum systems. By modulation the optical lattice depth, we successfully created a long-lived repulsively-bound pair of boson and fermion at the boundary of the phases spatially separated for bosons and fermions. The decay behavior will reveal novel properties of this phase boundary. We also obtained the signature of SU(6) Mott insulator. In addition, we revised our setup for generating the squeezed spin state via quantum non-demolition measurement, and improved the stability and reliability of the system.

Proposed research C02: Quantum information processing using an ion trap system

Project Leader: Shinji Urabe (Professor, Osaka University Graduate School of
Engineering Science)

We are carrying out the experiment for generating a Dicke state, which is an entangled state with symmetry against permutation of particles, by using rapid adiabatic passage. In this experiment, excitation of off-resonant sideband transitions with a high intensity beam is required, which causes significant AC stark shifts. We have prepared a setup for compensation of AC Stark shifts to avoid them and to generate Dicke states with high fidelity. In addition, we have completed a symmetric phase locking system using an optical comb, which is used for realizing robust quantum gates with stimulated Raman adiabatic passage.

Planar trap geometries where all electrodes are placed in a plane have substantial potential for realizing large-scale quantum information processing. We have developed a planar trap whose electrodes are gold, deposited on an alumina substrate. Calcium ions have been trapped and laser-cooled about 400 μm above the surface of the trap. We have also developed a method applicable to a planar trap for reducing the ion micromotion due to a stray electric field.

Research topic: Optical system quantum cybernetics

Proposed research D01: Realization of quantum cybernetics using photonic quantum circuits

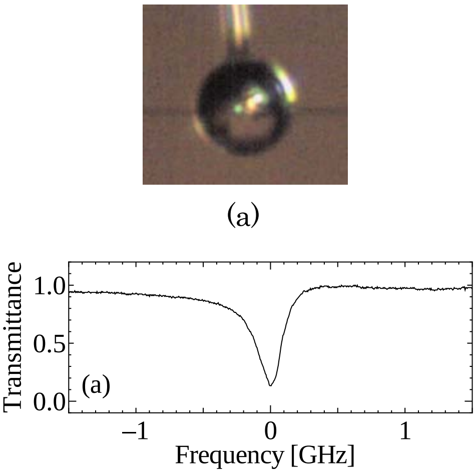
Project Leader: Shigeki Takeuchi (Professor, Institute for Electronic Science,
Hokkaido University)

Photons have excellent controllability and are easily interfaced with naturally occurring atoms and molecules as well as artificial atoms. So far, the largest quantum circuit combining linear optical devices and projection measurement has been realized. Our planning team aims to build a quantum-control combined test bed based on the concept of quantum cybernetics and achieve optimal quantum information control, particularly decoherent control. We also aim to achieve quantum state control between dissimilar quanta and to develop optical devices with built-in quantum control.

A single light emitter is a natural choice as a dissimilar quantum system interacting with a single photon. Namely, a diamond Nitrogen Vacancy (NV) center is attracting attention for its long phase coherence time and durability. For a highly efficient solid state optical resonator, a microsphere resonator coupled with a tapered fiber has been investigated. However, it has been difficult to control the distance between the tapered fiber and the microsphere at cryogenic temperature.

We have overcome the difficulty and successfully demonstrated the coupling between a microsphere (dia. 70 micrometer) and a tapered fiber (dia. 1 micrometer) at 8K (-265 ℃). We also confirmed the operation of the highly efficient optical micro resonator system with Q of 2 million using a probe laser beam at 638nm, which is the resonant frequency of a diamond NV center, for the first time as far as we know. This result is towards quantum state control between dissimilar quanta and to develop optical devices with built-in quantum control.

[1] Takashima et. al., Optics Express, vol. 18, No. 14, 15169 (2010).



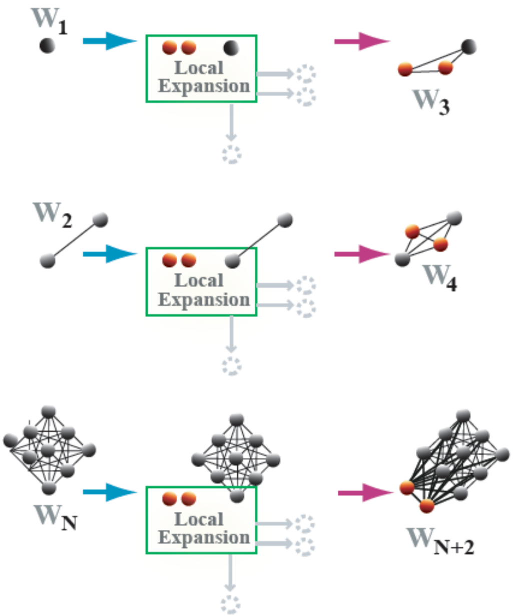
(a)

(b)

(a) Microsphere resonator coupled with a tapered fiber (b) Transmittance spectrum at 8K with a laser at 638nm.

Proposed research D02: Light-based multi-qubit quantum control

Project Leader: Masato Koashi (Associate Professor, Osaka University School of Engineering Science)



Quantum entanglement among many photons shows a wide variety of ways in which the photons can be correlated. Some entangled states retain a strong entanglement through correlations of all the photons as a whole, while others hold entanglement in a compartmentalized way that makes it more robust against loss of photons. 'W states' are the archetype of the latter, renowned for their strongest robustness against losses. Here we proposed and demonstrated a simple scheme for expanding the size of the W states by increasing the number of photons by two. Using the scheme, we have carried out expansion into three- and four-photon W states and successfully observed pair-wise entanglement that is characteristic of W states. The scheme is universal in the sense that it is applicable to any initial size of W states. It also involves only one photon in the initial W state. These make it a useful tool for growing entanglement to a large scale.