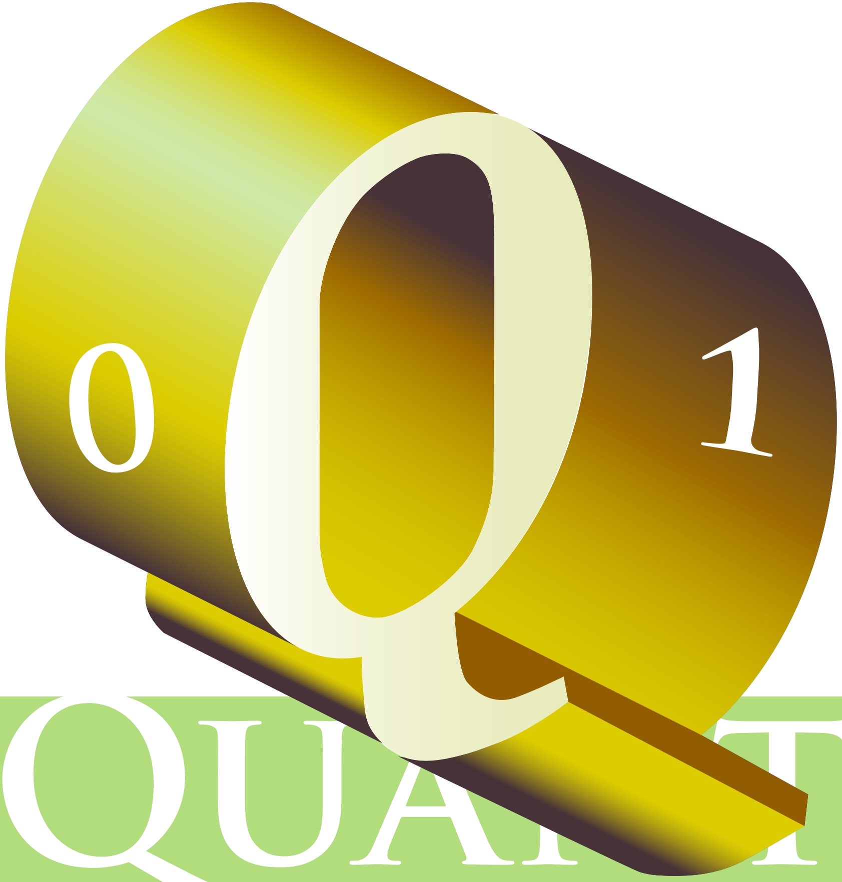


NEWS LETTER

Vol. 03

December 20, 2010

Science Research Grants from the Ministry of Education, Culture, Sports, Science and Technology — 2009 Grant-in-Aid for Scientific 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

Contents

Science Research Grants from the Ministry
of
Education, Culture, Sports and Science Technology
Scientific Research on Innovative Areas
「Quantum cybernetics — Interdisciplinary research on quantum control and its application to quantum computation」

Research Areas

<Superconducting system> Project leader : Jaw-Shen Tsai ··························2
RIKEN

<Semiconductor system > Project leader : Yasuhiro Tokura ··························3
NTT Basic Research Laboratories

<Molecular spin system> Project leader : Masahiro Kitagawa ··························4
Graduate School of Engineering Science, Osaka University

<Cold atoms system> Project leader : Yoshiro Takahashi ··························5
Kyoto University Graduate School of Science

<Ion trap system> Project leader : Shinji Urabe··························5
Osaka University Graduate School of Engineering Science

<Photonic system I> Project leader : Shigeki Takeuchi ··························6
Hokkaido University

<Photonic system II> Project leader : Masato Koashi ··························7
Osaka University School of Engineering Science

2010 Selected research proposals

<New development of quantum estimation theory in quantum cybernetic>
Project leader : Akio Fujiwara ··························8
Department of Mathematics, Osaka University

<Theory on quantum coherence in hybrid quantum system of superconductor and quantum dot> Project leader : Michiyasu Mori ··························8
Japan Atomic Energy Agency

<Study of single NV center in diamond toward scalable multi-qubit system>
Project leader : Norikazu Mizuochi ··························9
Osaka University Graduate School of Engineering Science

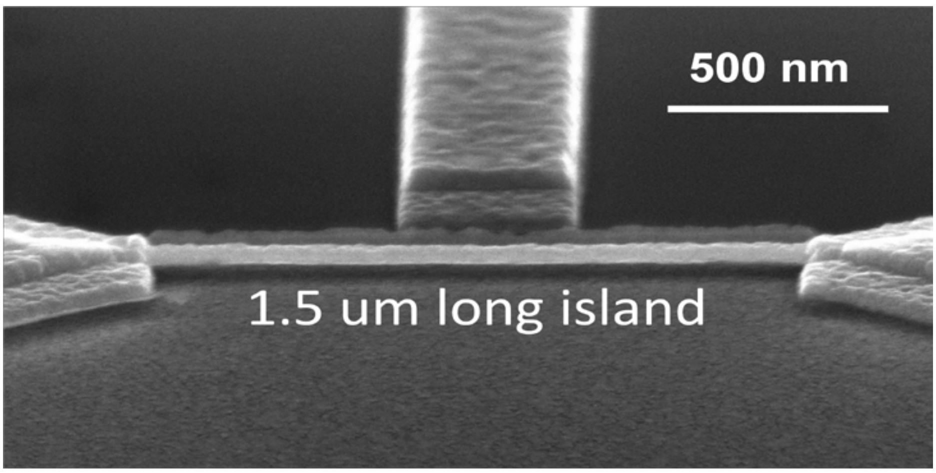
<Voltage-selective bi-directional nuclear spin polarization in semiconductor quantum dot device> Project leader : Keiji Ono ··························9
RIKEN

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)

We are carrying out studies of systems that consist of superconducting qubit and small mechanical resonators. Such systems have a potential of realizing quantum coherent control of the macroscopic mechanical oscillation mode. In below, some recent results in this research topic are described.

We have suspended an Al based single-electron transistor (SET) whose island can resonate freely between the source and drain leads forming the clamps (see picture in below). In addition to the regular side gate, a bottom gate with a larger capacitance to the SET island is placed underneath to increase the SET coupling to mechanical motion [1].



The device can be considered as a doubly clamped Al beam that can transduce mechanical vibrations into variations in the SET current. experimentally that a conventional SET in the dc regime can detect flexural motion of its own island. We observe the frequency response of the suspended SET driven by an rf voltage applied to the bottom gate. Our simulations based on the orthodox model, with the SET parameters estimated from the experiment, reproduce the observed transport characteristics in detail.

Damping causes the loss of quantum coherence, thus it is a very important subject to be studied. We have studied damping in polycrystalline Al nanomechanical resonators by measuring the temperature dependence of their resonance frequency and quality factor over a temperature range of 0.1–4 K [2]. Two regimes are clearly distinguished with a crossover temperature of 1 K. Below 1 K we observe a logarithmic temperature dependence of the frequency and linear dependence of damping that cannot be explained by the existing standard models. We attribute these phenomena to the effect of the two-level systems characterized by the unexpectedly long relaxation times and discuss possible microscopic models for such systems. We conclude that the dynamics of the two-level systems is dominated by their interaction with one-dimensional phonon modes of the resonators.

[1] ***"Detection of mechanical resonance of a single electron transistor by dc current"***
Applied Physics Letters, 96, 263513, 2010
[2] ***"Damping in high-frequency metallic nanomechanical resonators"***
Physical Review B81, 184112, 2010

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

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

Electron spin confined in quantum dots (QDs) is a promising candidate as an element of qubit system. Aiming at realizing a three spin-qubit system using a slanting-field method, we designed split micromagnets (MMs) suitable for the lateral triple quantum dots and fabricated such a triple quantum dot to test its performance. Note we have already demonstrated a two-spin qubit system, and the realization of a three qubit system is a necessary step for scaling up the qubit system.

Electron spin resonance (ESR) is the fundamental tool for spin qubits, and usually requires a dc and an ac magnetic field normal to each other. In the slanting-field method with an in-plane external magnetic field, an ac magnetic field is effectively generated by electrical oscillation of an electron inside a QD under a gradient of the *out-of-plane* stray field imposed by a MM located above. This MM also provides an *in-plane* stray field local to each QD. This technique, therefore, allows us to address single spins in multiple QDs with electrically driven ESR at different resonance frequencies.

There are two demands for designing the MMs; the first is to keep the Zeeman-energy difference between adjacent QDs large enough compared to the broadening of each ESR peak due to the fluctuating nuclear field in GaAs materials. The second is to make the slanting field, which is proportional to the Rabi frequency, as large as possible for faster qubit operations.

Based on this idea, we designed MMs, which enable the electrical and addressable manipulation of three qubits. Furthermore, we proved this technique could be applied up to 25 qubits in realistic multiple QDs. As a first step toward implementing such three-qubit systems, a relevant triple QD device has been fabricated and characteristic charge states were observed. In the future we will combine the triple QD and designed MMs to implement three spin qubits.

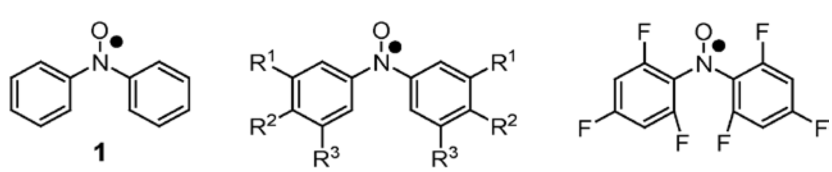
Research topic: Molecular spin quantum cybernetics

Proposed research B01: Molecular spin quantum control

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

Molecular Designs for the Increase in the Number of Client Nuclear Qubits in Synthetic Electron-Spin Bus Qubit Systems.

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 the mixture of matter spin qubits with intrinsically different nature of spins. In view of any implementation of molecular spin quantum cybernetics, molecular designs and materials syntheses relevant to electron-spin bus qubits with distinguishable client qubits as many as possible have been the focus of current issues among the diverse topics in molecular-spin based QC/QIP. We have shown that molecular spins enjoy significant advantages in terms of synthetic-qubit designs and control of hyperfine tensors or hyperfine coupling constants (*A*-tensor engineering). During the last several months in the 2010 academic year, we have established particular molecular designs for increasing the number of client nuclear qubits, which are well-defined and identified in terms of the corresponding hyperfine tensors/coupling constants. We have chosen stable diphenylnitroxide (DPNO) **1** as an efficient bus molecular skeleton, as depicted in Figure. ^{19}F nucleus is a suitable candidate for a client qubit because of its large nuclear gyromagnetic ratio. We have introduced ^{19}F nuclei into the DPNO skeleton at particular positions of the phenyl rings, experimentally determining their hyperfine coupling constants by invoking Electron-Nuclear Double/Triple Resonance spectroscopy in solution. To complete chemical identifications, we have carried out quantum chemical calculations for all the fluorinated DPNO derivatives and obtained their spin-Hamiltonian parameters, comparing those with the experimental parameters in terms of the magnitude and sign. The results show that DPNO, and the derivatives **2a**, **2b** and **3**, as depicted in Figure, are assigned as three-client qubit, three-client qubit, six-client qubit, respectively. It is notable that the number of the client qubits is not interpretable in terms of the putative general principle for the identification of hyperfine coupling constants in π-electron network systems such as DPNO. We have illustrated that spin delocalization induced by the introduction of fluorines dominates spin polarization in the π-electron network system. (321 words)



1

2a: $R^1 = R^3 = F$, $R^2 = H$
b: $R^1 = R^2 = F$, $R^3 = H$

3

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 created in a thin glass cell region into a 3D optical lattice to suppress the mean-field broadening of the spectrum. In fact, we successfully observed the very narrow excitation spectrum which is limited by the finite laser linewidth using the ultra-narrow optical transition. In addition, we successfully obtained the resonance from the two atoms per lattice site, which is largely shifted from the resonance from one atom per lattice site. From these spectra we can get the direct information on the interatomic interaction.

We also successfully cooled the Fermi-Fermi mixture of Yb atoms for quantum simulation. This system is very attractive because it has high-spin symmetry of $SU(6) \times SU(2)$.This work was published as Physical Review Letters**105**, 190401(2010) with Editor's Suggestion. Also in AIP, Viewpoint、with the title of "Exotic many-body physics with large-spin Fermi gasses" Dr. Congjun Wu wrote an introductory 2-page article(Physics **3**, 92(2010)).

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

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

We have developed a new method of sensitive detection of excess micromotion for planar traps since an already established method for conventional ion traps cannot be applied to planar traps. The excess micromotion due to a stray electric field is a serious problem because the ions are not sufficiently laser-cooled in the presence of the excess micromotion then the phonon state cannot be well-controlled. Therefore, sensitive detection of the excess micromotion and application of a compensation voltage are required. Since the access of a laser beam is restricted in planar traps, the conventional method cannot be applied. We proposed that modulation of the trap potential allows us to detect the excess micromotion regardless of laser propagation direction. The micromotion compensation in a planar trap was experimentally realized by using this method.

The methods that have so far been used for generation of entangle states of atoms have depended sensitively on experimental parameters such as pulse widths or intensity. With the adiabatic method we use, we can expect robustness against change of such parameters, which we have explicitly verified for the first time. In experiments in which the width of optical pulses and their maximum Rabi frequency were varied, we observed that the fidelity changed by less than 10%. The inseparability condition was always met so that the ions were always entangled. Toward quantum information processing using trapped ions without suffering from spontaneous emissions, we have performed quantum gate experiments using RF magnetic fields, and have demonstrated a Cirac-Zoller gate using the internal and motional states of one ion. We also have performed experiments on generation of entangle states of two ions using the Molmer-Sorensen method, and have succeeded in generating Bell states with fidelity of 0.76.

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)

Daiwa Adrian Prize 2010 awarded to a leader of the team in Quantum Cybernetic Project.

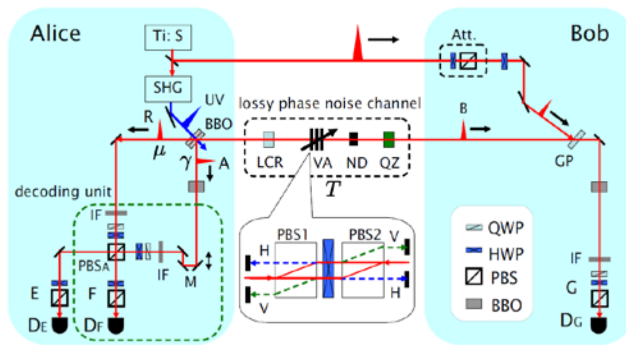
Photons have excellent controllability and are easily interfaced with naturally occurring atoms and molecules as well as artificial atoms. So far, the largest quantum circuit combining linear optical devices and projection measurement has been realized. Our planning team aims to build a quantum-control 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.
Prof. Shigeki Takeuchi, the team leader of D01 group of Quantum Cybernetics Project, received Daiwa Adrian Prize 2010 together with Prof. Jeremy O'Brien at University of Bristol for `Photonic quantum information science and technology. Development of new technologies based on harnessing quantum mechanics – the fundamental physics theory governing behavior at the microscopic scale'. Daiwa Adrian Prizes are awarded by The Daiwa Anglo-Japanese Foundation on a triennial basis in recognition of significant scientific collaboration between British and Japanese research teams, following an assessment conducted by a panel of Fellows of the Royal Society. The Prize Ceremony was held on December 2, 2010 at the Royal Society, London. This award encourages the further fruitful collaborations between the scientists in the UK and Japanese involved in this Quantum Cybernetics Project.

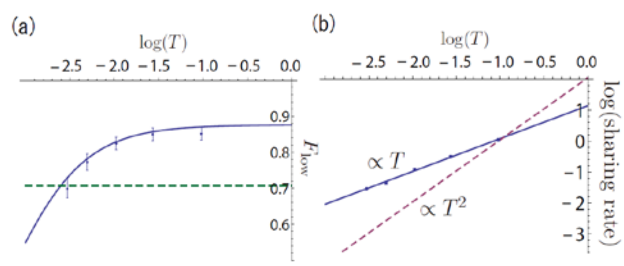
Daiwa Adrian Prizes 2010 Presentation Ceremony the Royal Society.
From the left, Prof. Takeuchi, Lady Adrian, and Prof. O'Brien.

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

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

Distribution of entanglement among distant parties is essential in various quantum communication tasks, and it is important to accomplish it over realistic quantum channels with a lot of noisy fluctuations. Decoherence free subspace (DFS), which is available when we encode quantum information onto multiple photons, is known to be a convenient way of bestowing protection against slow fluctuations. But the use of n photons means that all of them must pass through the channel which is lossy, resulting in a rapid decrease in the efficiency scaling as $O(T^n)$ with channel transmission T. We have proposed and demonstrated a new method of using a two-photon DFS to overcome this drawback, namely, achieving the efficiency of $O(T)$ instead of $O(T^2)$. In this method, the symmetry of the entangled state is used to 'swap' the photons encountering the channel noise, which allows us to replace a single photon with a coherent state that is more robust against losses. We have succeeded in achieving the success probability of $O(T)$ with the final fidelity of ~ 0.8.





2010 Selected research subjects and project managers

Proposed research 01: New development of quantum estimation theory in quantum cybernetics

Project Leader: Akio Fujiwara (Professor, Department of Mathematics, Osaka University)

Quantum estimation theory is a branch of noncommutative statistics that addresses the problem of finding the best estimation procedure for an unknown quantum object by a physically feasible measuring process. Recently, we studied the efficiency of quantum state tomography from the point of view of quantum parameter estimation theory, in which we seek an estimator that minimizes the trace of the weighted covariance. It was shown that tomography is optimal when and only when a physically quite unnatural type of weight is adopted. For more information, see: quant-ph:1010.3813.

Proposed research 03: Theoretical study on quantum coherence generating from coupling between quantum dot and superconductor

Project Leader: Michiyasu Mori (Senior Assistant Researcher, Japan Atomic Energy Agency)

Josephson junction irradiated with microwave shows a current-voltage characteristics like as staircase, which is called Shapiro steps. The current-steps appear at the voltages linked to the microwave frequency by the universal constant ($\hbar / 2e$). This means that the voltage is determined only by the microwave frequency. Since the microwave frequency can be controlled very accurately (~10^{-12}), the voltage is also determined in the surprising accuracy (~10^{-9}). The voltage standard around the world is established by this principle.

In this project, we aim to apply a hybrid quantum system of superconductor and quantum dot to the quantum computing devices and the quantum standards. In particular, it must be important to control quantum states generating from the coupling between the superconducting phase and the electron spin in the quantum dot. Therefore, we consider that "ferromagnetic Josephson junctions", in which two superconducting electrodes are separated by a ferromagnet, would be a useful reference. It is noted that the ferromagnetic Josephson junction is one of candidates to be a quantum computing device. Previously, we found that the ferromagnetic Josephson junctions applied with AC magnetic field shows a stepwise current-voltage characteristics[1]. In this case, unlike the above Shapiro step, the ferromagnetic resonance frequency is linked to the voltage. Hence, it will provide a new principle of quantum standard on magnetism. In order to use the spin states and the superconducting phase, it is essential to study the quantum coherence under the external field.

Recently, we have found a hybrid excited state resulting from coupling between spin-wave and electromagnetic field induced in the ferromagnetic Josephson junction by the AC Josephson current, which is generated by the DC voltage applied to the junction[2]. In this case, the junction itself behaves as resonator. When the frequency of AC Josephson current matches to the resonance frequency of junction, the DC Josephson current is induced. This phenomenon is called Fiske resonance. In our study, unlike the usual Fiske resonance, the multiple resonance appears for each resonant mode in the junction, since the spin-wave is excited by the electromagnetic field. In addition, it is found that such a multiple resonance is identified to be hybrid excited state, which is a mixture of spin and electromagnetic waves. Our results are now under examination by several experiments[3].

[1] S. Hikino, M. Mori, S. Takahashi, and S. Maekawa, J. Phys. Soc. Jpn, 77, 053707 (2008)
[2] S. Hikino, M. Mori, S. Takahashi, and S. Maekawa, arXiv:1009.3551.
[3] I. Petković, Ph.D. thesis, Université Paris-Sud, 2009.

Proposed research 04: Study of single NV center in diamond toward scalable multi-qubit system

Project Leader: Norikazu Mizuochi (Associate professor, Graduate School of Engineering Science, Osaka University)

In this project, we would like to develop the number of qubits of the subsystem and techniques toward the interaction between subsystems. For local coupling, we would like to develop by using the coupling between nuclear spin and electron spin. Recently, we are trying to demonstrate the quantum algorithm in multi-qubit system of single NV center.

Proposed research 05: Manipulation of electron spin and nuclear spins in hetero-g-factor double quantum dot

Project Leader: Keiji Ono (Low Temperature Physics Laboratory, RIKEN)

Voltage-selective bi-directional nuclear spin polarization in semiconductor quantum dot devices

We studies electrical control of nuclear spins in quantum dots that can potentially be used as a quantum memory for spin qubits. Recently we have achieves that the nuclear spins can be strongly polarized in either of two opposite directions. The direction is selected by adjusting the voltage of the device. This work confirmed that the nuclear spins in quantum dots are indeed long-lived quantum states with a coherence time of up to 1 ms, and may be a promising resource for quantum information processing such as quantum memories for electron spin qubits.

Double quantum dots in the spin blockade regime are used to prove a nuclear spin in quantum dots. Repeated transition from the spin-blocked triplet state to unblocked singlet state can be induced by the hyperfine flip-flop scatterings with the nuclei in the quantum dots. Detection of nuclear state is measured via the "recovery time" of the leakage current in the spin blockade state. Tuning the voltage of the device selectively induce the spin scattering from T− triplet to singlet, as well as the spin scattering from T+ triplet to singlet. These selective spin scattering lead to bi-directional nuclear polarization.