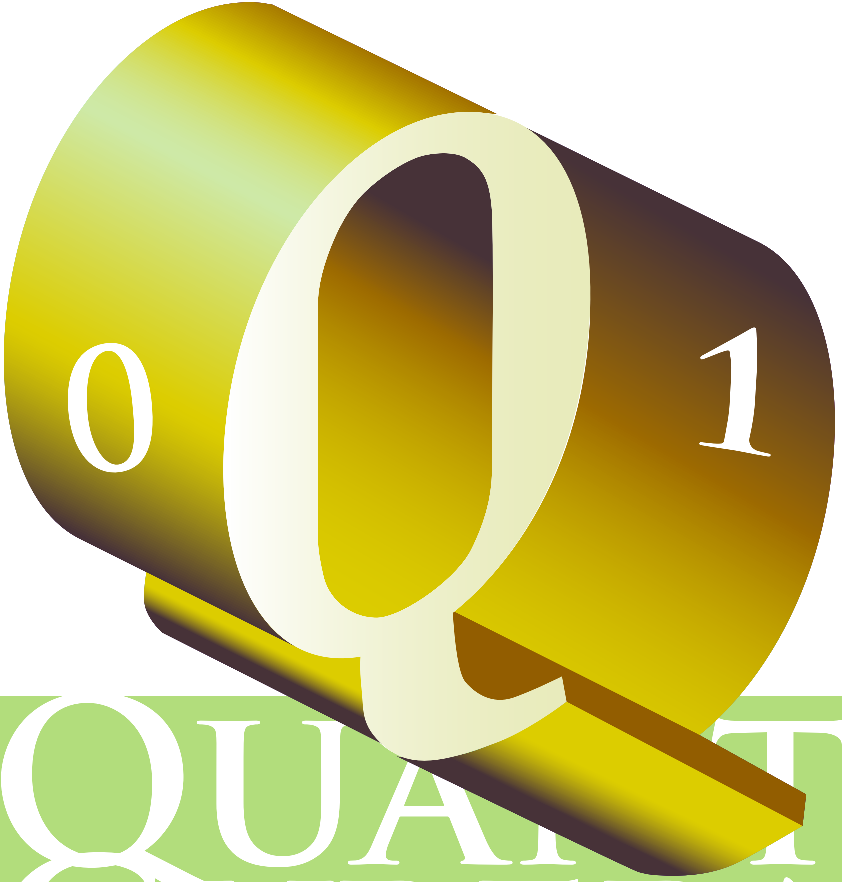

NEWS LETTER

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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

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Research topic A: Solid-state device quantum cybernetics

Proposed research A01: <u>Study of superconducting quantum cybernetics</u>
Project Leader: Jaw-Shen Tsai (Team Leader, RIKEN; Senior Researcher, NEC Smart Energy Laboratory)

―ZcQED: a scalable architecture for superconducting qubits

So far, circuit QED has been dealing with artificial atoms coupled transversely (ie. *via* s_x) to one or few bosonic modes: we introduce a new paradigm wherein an artificial atom is coupled longitudinally (ie. *via* s_z) to a quantum harmonic oscillator which we call ZcQED, akin to trapped ions systems in atomic physics. We find that this system is free of dispersive shift when the qubit is operated at its symmetry point, and we reveal the possibility to perform single-qubit operations and sideband transitions at any order when the qubit is driven transversely, with the same nonlinearity of the matrix elements as a function of the photon states which is found in ion-traps [1]: a main difference however is the presence of a fixed coupling between the qubit and the resonator which introduces some static residual interactions between physical qubits ($s_z s_z$ type). We devise an architecture to process quantum information based on this new layout, inspired by the ideas developped in trapped ions experiments: a noticeable difference in ZcQED is the possibility to achieve rather strong atom-photon coupling. This naturally brings us to operate such system out of the Lamb-Dicke regime, and to look for ways to overcome the limitations imposed by the nonlinearity of the Jaynes-Cummings model in this configuration [1].

We are considering a 2D array of qubits with nearest-neighbor interactions, motivated by the possibility to use the surface code to realize error correction. In order to cancel the residual interactions between each pair of neighboring physical qubits, we couple them *via* two resonators fixedly coupled in series. This extra degree of freedom in the system allows to realize sideband transitions while ensuring an intrinsic protection against the leakage of information out of the computational subspace, even though we are working out of the Lamb-Dicke regime. It also brings the possibility to readout the state of the qubits following the proposal by Englert *et al*. inspired from electron shelving [2].

[1] W. Vogel and R. L. de Matos Filho, Phys. Rev. A **52**, 4214 (1995).
[2] B. G. U. Englert, G. Mangano, M. Mariantoni, R. Gross, J. Siewert and E. Solano, Phys. Rev. B **81**, 134514 (2010).

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

Project Leader: Yasuhiro Tokura (Professor, Graduate School of Pure and Applied Science, University of Tsukuba)

The Kondo effect, an archetype of many-body correlations, arises from the interaction between a localized spin and surrounding conduction electrons. It is characterized by a many-body singlet ground state. Scattering through the Kondo ground state is well described by Nozières' Fermi liquid theory [1]. When an electron of sufficiently low energy is incident on the impurity in the screened singlet state at low temperature, it is coherently scattered off into a single quasi-particle acquiring a $\pi/2$ phase shift, but with zero probability for a spin flip. This $\pi/2$ phase shift can be viewed as a fingerprint of spin screening and is thus one of the most fundamental properties of the Kondo many-body ground state. Experimental difficulties, however, have prevented an unambiguous observation of this $\pi/2$ phase shift.

Our newly developed solid state two-path interferometer consisting of an Aharonov-Bohm (AB) ring and two tunnel-coupled wires allows for direct and precise measurement of the transmission phase shift, by observing output flying qubit states defined by the presence of propagating electrons in either of the two wires. [2]. In addition, such phase measurements only collect coherent processes, i.e. single particle scattering without spin flip. The linear relationship between the energy and the phase leads to cancelation of thermal distribution above and below the Fermi energy, allowing to obtain $\pi/2$ phase shift predicted for the low temperature limit even at high temperatures up to the Kondo temperature T_K. We observed for the first time a clear $\pi/2$ phase shift up to $T \sim T_K$. Above T_K, the phase shifts by more than $\pi/2$ at each Coulomb peak, approaching the behavior observed for the standard Coulomb blockade regime characterized by the Friedel's sum rule. We compared these results with numerical renormalization group calculations and found remarkable agreement. Our work also indicates that flying qubit states are controlled with very high precision in the two-path interferometer.

[1] P. Nozières, Journal of Low Temperature Physics **17**, 31 (1974).
[2] M. Yamamoto, S. Takada, C. Bäuerle, K. Watanabe, A. D. Wieck and S. Tarucha, Nature Nano. **7**, 247 (2012).

Research topic B: Molecular spin quantum cybernetics

Proposed research B01: Molecular spin quantum control
Project Leader: Masahiro Kitagawa (Professor, Graduate School of Engineering Science, Osaka University)

—Pulsed electron spin nutation spectroscopy and NMR paradigm ESR spin technology for weakly exchange-coupled multi-spin molecular systems with nuclear hyperfine couplings: A general approach to bi- and tri-radicals and determination of their spin dipolar and exchange interactions

Reported by T. Takui, Group of "Control of Molecular Spins"

Weakly exchange-coupled biradicals have attracted much attention in terms of their DNP application in NMR spectroscopy for biological systems or the use of synthetic electron-spin qubits in quantum information processing/quantum computing technology. Analogues multi-partite molecular systems are important in entering a new phase of the relevant fields. Many stable organic biradicals known so far have nitrogen nuclei at their electron spin sites, where SOMOs (Singly Occupied Molecular Orbitals) are dominating and large hyperfine couplings occur. A salient feature of such weakly exchange-coupled molecular systems in terms of electronic spin structures is underlain by small zero-field splitting (ZFS) parameters comparable with nuclear hyperfine and/or exchange interactions. Pulse-based electron spin nutation (ESN) spectroscopy of weakly exchange-coupled biradicals, applicable to oriented or non-oriented media, has proven to be a useful and facile approach to the determination of ZFS parameters, which reflect relatively short distances between unpaired electron spins (K. Ayabe *et al.*, Phys. Chem. Chem. Phys. **14**, 9137 (2012)). In the present study, we first treat two-dimensional single-crystal ESN spectroscopy (Q-band) of a ^{15}N-labelled weakly exchange-coupled biradical, showing the nuclear hyperfine effects on the ESN phenomena from both the experimental and theoretical side. ESN spectroscopy is transition moment spectroscopy, in which the nutation frequency as a function of the microwave irradiation strength ω_1 (angular frequency) for any cases of weakly exchange-coupled systems can be treated. The results provide a testing ground for the simplified but general approach to the ESN analysis. In this study, we have invoked single-crystal ELDOR measurements on a typical biradical well incorporated in a diamagnetic host lattice and checked the accuracy of our ESN analysis for the spin dipolar tensor and exchange interaction. Next, we extend the general approach to analogues multi-partite molecular systems such as stable organic triradical, in which the exchange interaction can be governed by a significant amount of the delocalisation of three unpaired spins over the molecular frame of a triangular structure. The triangular structure maintains p-conjugation in which each spin-bearing nitroxide at the vertex participates and the exchange interaction is greatly controlled by the dihedral angle between the p-conjugation plane and nitroxide moiety at the vertex. In this context, the ZFS parameters do not correspond to spin distances (1.0 nm) in a straightforward manner, but reflect a salient electronic structure associated with both the p-electron network and the symmetry property of the triradical under study. Thus, both the D-value and exchange interaction J have been controlled in this study. In order to interpret the experimental ZFS parameters and exchange interaction, which is three-order of magnitude reduced in the present poly(methyl methacrylate) polymer matrix compared with that in the crystal, sophisticated quantum chemical calculations of the ZFS tensor and exchange interaction were carried out and reproduced the experimental values, concluding that the present triradical of the triangular structure undergoes significant twisting at the nitroxide sites in the polymer matrix. In this study, we observed ESR forbidden transitions between the *M*s-manifolds belonging to the spin-doublet ground state and spin-quartet excited state. The observation enables us to derive the magnitude of the exchange coupling. The method implemented in our lab. is particularly useful for the characterization/identification of molecular multi-spins which serve as test beds for molecular spin based QC/QIP and in quest of open shell entities for their DNP applications.

We have recently implemented NMR paradigm based ESR spin technology applicable to the manipulation of both electron bus qubits and nuclear spin client qubits in molecular frames by using AWGs.

[1] Kazuki Ayabe, Kazunobu Sato,* Shigeaki Nakazawa, Shinsuke Nishida, Kenji Sugisaki, Tomoaki Ise, Yasushi Morita,* Kazuo Toyota, Daisuke Shiomi, Masahiro Kitagawa, Shuichi Suzuki, Keiji Okada* and Takeji Takui*, “Pulsed electron spin nutation spectroscopy for weakly exchange-coupled multi-spin molecular systems with nuclear hyperfine couplings: A general approach to bi- and tri-radicals and determination of their spin dipolar and exchange interactions”, *Mol. Phys.*, **111**, 2767-2787 (2013).

http://dx.doi.org/10.1080/00268976.2013.811304

Research topic C: Atomic and ionic system quantum cybernetics

Proposed research C01: <u>Quantum control using cold atoms</u>
Project Leader: Yoshiro Takahashi (Professor, Atomic Physics, Graduate School of Science, Kyoto University)

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. The recent achievements are in the followings.

Firstly, we have successfully developed a frequency-stable laser for an ultranarrow optical transition of ytterbium atoms, which is useful for ultimate quantum measurement and quantum state control and high-resolution probe of the quantum gas. By measuring the beat frequency stability between two similarly developed lasers, we confirmed that the laser line width was reduced down to about 3Hz. This laser will improve the spectral resolution by about 300 times compared with the previous one, and will be applied for many studies.

Furthermore, while we have so far separately developed a high-spatial resolution imaging method and high-frequency-resolution spectroscopic method for ultracold atoms in an optical lattice, recently we successfully combined these two ultimate methods and succeeded in developing a “spectral imaging” method for a single layer of two-dimensional quantum gas. We revealed the subtle spatial inhomogeneity of the optical lattice potential by exploiting a high resolution spectroscopy using ultra narrow optical transition, and also successfully performed a magnetic resonance imaging of the quantum gas by applying a magnetic field gradient in the two dimensional plane. We hope to apply this method for observing edge states of topological superfluids, and so on.

Proposed research C02: <u>Quantum information processing using an ion trap system</u>
Project Leader: Shinji Urabe (Professor, Graduate School of Engineering Science, Osaka University)

―Improvement in the coherence time of the laser for excitation of the qubit transition

Multipartite entanglement is what characterizes quantum mechanics and can be considered as a resource in quantum information processing. So far multipartite entangled states (GHZ states) with 14 particles have been realized in ion trap systems. Our group has tried to generate multipartite entangled states called Dicke states, which are in a class different from GHZ states, and has succeeded in generation of 4-partite entangled states. In such generation of multipartite entanglement, decoherence due to coupling to the environment or dephasing due to fluctuation of system parameters may deteriorate the generation fidelities, and hence we have continuously struggled with suppression of such effects. This time we have succeeded in improving the coherence time of the laser for excitation of the qubit transition of calcium ions. More explicitly, we stabilized the output frequency of a ring titan sapphire laser to the resonance frequency of a Fabry-Perot cavity which was made of an ultra-low-expansion glass material using the digital signal processing technology. We illuminated the output of this laser to a single calcium ion, and performed a Ramsey interferometry experiment, obtaining a coherence time of 20 ms. This corresponds to a 8 Hz linewidth. From measurements using multiple Zeeman components, we infer that the effect of the fluctuation of magnetic fields dominates this linewidth, and estimate the contribution of the fluctuation of the laser frequency to be on the order of 1 Hz. We are planning to use this laser in experiments on generation of multipartite entanglement. We expect that this stable laser is also effective in experiments of quantum simulation and the research of a calcium-ion optical frequency standard.

Research topic D: Optical system quantum cybernetics

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

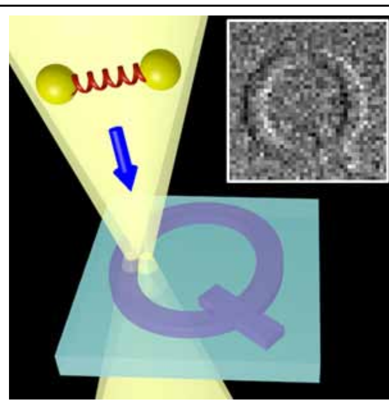
Project Leader: Shigeki Takeuchi (Professor, Institute for Electronic Science, Hokkaido University)

Photons have excellent controllability and are easily interfaced with naturally occurring atoms and molecules as well as artificial atoms. Our planning team aims to control photonic quantum state and explore new concepts in terms of quantum cybernetics. We also aim to achieve quantum state control between dissimilar quanta and to develop optical devices with built-in quantum control.

Among the applications of optical phase measurement, the differential interference contrast microscope is widely used for the evaluation of opaque materials or biological tissues. However, the signal-to-noise ratio for a given light intensity is limited by the standard quantum limit, which is critical for measurements where the probe light intensity is limited to avoid damaging the sample.

We proposed to use an entangled photons to beat this standard quantum limit. We have demonstrated an entanglement enhanced microscope, which is a confocal-type differential interference contrast microscope where an entangled photon pair source is used for illumination. An image of a Q shape carved in relief on the glass surface is obtained with better visibility than with a classical light source. The signal-to-noise ratio is 1.35±0.12 times better than that limited by the standard quantum limit. The success of this research will enable more highly sensitive measurements of living cells and other objects, and it has the potential for application in a wide range of fields, including biology and medicine.

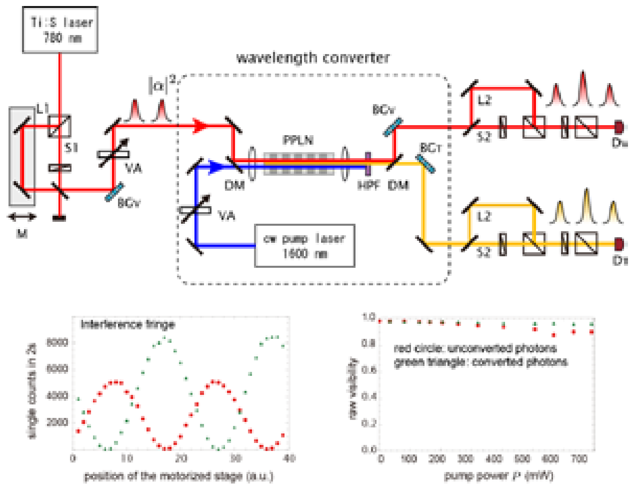
[1] T. Ono, R. Okamoto, S. Takeuchi, An entanglement-enhanced microscope. *Nat. Commun.*4, 2426 (2013).



An Image of glass plate sample obtained by an entanglement-enhanced microscope

Proposed research D02: <u>Light-based multi-qubit quantum control</u>
Project Leader: Masato Koashi (Professor, Photon Science Center of the University of Tokyo)

―Coherent partial wavelength converter for a single photon



A photonic quantum interface for a wavelength conversion has recently attracted much attention as a tool to change the wavelegth of a photon while preserving the quantum information it carries. The wavelength conversion between two optical fields through a nonlinear optical medium with a sufficiently strong pump light is described by an effective Hamiltonian of a beamsplitter in a frequency domain. As the first step toward a new type of beamspiltter working at quantum level, we partially converted temporally-separated two coherent light pulses with average photon numbers of ~0.1 at 780 nm to light pulses at 1522 nm via periodically-poled lithium niobate waveguide pumped at 1600 nm. We demonstrated that two output light pulses of different wavelengths (780 nm and 1522 nm) after wavelength conversion inherit phase information of the input light with high visibilities. We observed that interference visibilities at various conversion efficiencies R are no less than 0.88 for both wavelengths. At R=1/2 the visibility was as high as 0.98. Such a wavelength converter will be useful for manipulating quantum states encoded in the frequency degrees of freedom. [R. Ikuta, et. al., Opt. Express 21, 27865 (2013).]

2012 Selected research subjects and project managers

Proposed research 02: Classical Compilers for Topological Quantum Information Processing

Project Leader: Simon Devitt (Assistant Professor, Quantum Information Science group, National Institute for Informatics)

Our recent work into circuit optimisation and compilation for large-scale, topological quantum computation has allowed us to perform a detailed and fully complete resource estimate for a large quantum algorithm. The results of the study, published in the journal Nature Communications, reveal the number of physical devices and the amount of time required to execute Shor's algorithm for factoring numbers on a quantum computer built from realistic hardware. We illustrate what a complete resource analysis for a quantum computation requires and explicitly take into account all aspects of an error corrected computation. We show that classical circuit optimisation, rather than more accurate quantum hardware has the greatest potential to minimise resources for large quantum algorithms.

Proposed research 03: <u>Study of the initialization of an electron spin</u>

Project Leader: Yasuaki Masumoto (Professor, Graduate School of Pure and Applied Science, University of Tsukuba)

―Trion resonant Kerr rotation in ZnO:Ga

Spins of localized electrons in semiconductors are expected for spin quantum memory matching polarized light well for quantum communication. Their spin coherence time is restricted by the fluctuating nuclear magnetic field. Non-zero nuclear spins of constituent atoms in ZnO are smallest in the natural abundance among II-VI semiconductors, which lengthens the spin coherence time of localized electrons. Femtosecond time-resolved Kerr rotation and resonant spin amplification verified the long spin coherence time, T_2*=12ns, of localized electrons in Ga-doped ZnO ($6 \times 10^{17} cm^{-3}$). The 2ps time-resolved Kerr rotation, on the other hand, clarifies the resonant excitation profile with spectral resolution of 0.2meV at the lower energy tail of the A-exciton including sharp D^0X resonance. Nearby the A-exciton and D^0X resonance, Kerr rotation signal by electrons (period=74ps under the magnetic field of 0.5T) is enhanced and changes the sign. Especially, the spin rotation of electrons is doubly enhanced around the D^0X luminescence energy, T, and T-D, where D is 2-4meV. Further, around the D^0X resonance Kerr rotation signal contains fast oscillation (period=19ps) at the initial rise part of the signal, suggesting the quantum beat coming from the fine energy splitting of 0.2meV. Fine energy structure of the trion composed of 2 electrons and a hole is considered to explain the picosecond Kerr rotation signal around the D^0X resonance in ZnO:Ga.

Proposed research 04: <u>Development of element technologies and elucidation of physics toward realization of silicon quantum bits</u>

Project Leader: Tetsuo Kodera (Assistant Professor, Quantum Nanoelectronics Research Center, Tokyo Institute of Technology)

Study of quantum computation using spins in quantum dots (QDs) has been led by GaAs systems so far. However, it needs to be expanded to silicon-based QD systems in the future when a problem of decoherence due to nuclear spins and the compatibility to the current technologies of electronics are taken into account. In order to advance more rapidly this research, it is essential to successfully apply the technologies and the findings which have been obtained in GaAs QD systems, to silicon QD systems. In this study, we design and fabricate silicon QD devices in a few-electron regime and characterize the transport properties. In addition, we aim spin manipulation and readout by high-frequency voltage operation on the basis of experiences in GaAs QDs.

We studied transport properties of silicon double QDs coupled in series with a QD charge sensor. Devices are lithographically-defined Si QDs with the top gate (TG) for tuning carrier density and the side gates for controlling QD-potentials. A non-doped Si-on-insulator (SOI) wafer instead of a heavily-doped n-type SOI wafer was used in order to avoid localized states due to fluctuation of dopant potentials. We measured the current thorough the charge-sensor while sweeping two side gates of the double QDs. As a result, honeycomb-like charge stability diagram in a few-electron regime was obtained. In addition, by performing the voltage pulse control, Pauli spin blockade was successfully observed. In specific number of electron regimes, tunneling related to valleys as well as spins will be observed. We will study the relaxation time between two different valleys.

Proposed research 05: <u>Quantum non-equilibrium statistical physics and thermodynamics in the control and detection of quantum coherent processes</u>

Project Leader: Yasuhiro Utsumi (Associate Professor, Department of Physics Engineering, Faculty of Engineering, Mie University)

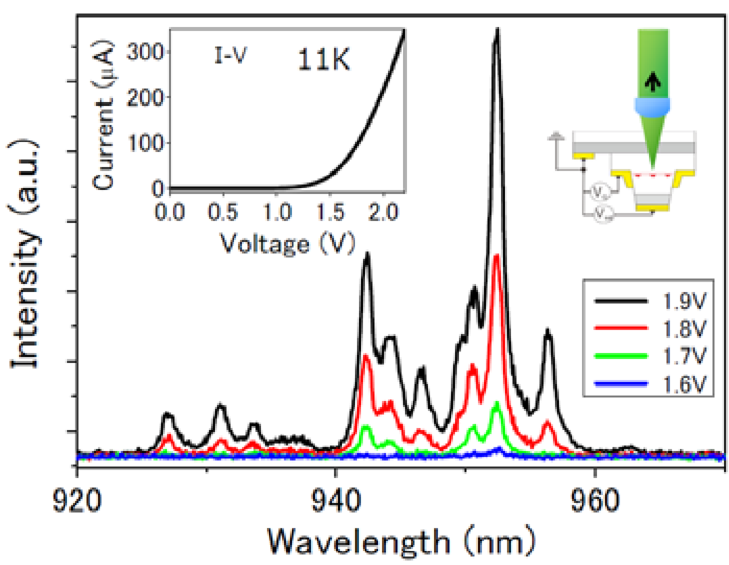
Recently it became possible to control and detect coherent quantum systems, such as charge, flux and spin qubits. Independently, the statistical physics and the thermodynamics in mesoscopic systems have been progressed and an exact relation valid in non-equilibrium regime, “the fluctuation theorem” has been discovered. The theorem is formulated based on the distribution of non-equilibrium fluctuations induced by a driving force. For now, measurements of probability distributions of current and work using single-electron transistors have been realized and the fluctuation theorem has been verified experimentally. However those experiments are still in the “classical” regime. The aim of this project is to extend them to the quantum regime.

Until now, we have theoretically analysed several issues, which should be clarified in order for the verification of the quantum fluctuation theorem. We are now considering an experimental setup to demonstrate the quantum fluctuation theorem using a solid-state qubit. As a theoretical model, we take a general two-state model coupled to a bosonic bath. Then we are constructing the theory of full-counting statistics for the probability distribution of heat emitted to the bath under particular initial and final states. Especially we are interested in a protocol to be robust against the 1/f noise.

Proposed research 06: <u>Research on charge-state controlled single-photon device toward realizing long-distance transfer of electron spin state</u>

Project Leader: Toshihiro Nakaoka (Associate professor, Faculty of Science, Sophia University)

In this project, we aim to develop basic techniques and fabrication of compact device based on an electrically excited quantum dots for generating remote entanglement. Recently, we have successfully fabricated the quantum-dot light-emitting-diode (LED) with a side gate. The gate is designed to generate exciton states for producing entangled states between the frequency of an outgoing photon and an electron spin state. The lower figure shows the current-voltage curve and the electroluminescence spectra of the quantum dot LED. The spectra have been measured by a method developed in this project for efficient optical access from the substrate-side (backside) of our device covered with the source-drain and side-gate electrodes. The results demonstrate the developed measurement method and the fabricated LED works well. We are optimizing the measurement setup and the fabrication processes.



Proposed research 07: <u>Toward Manipulation of Quantum Spin Information in Biomolecules</u>

Project Leader: Hideto Matsuoka (Senior Scientist, Institute of Physical and Theoretical Chemistry, University of Bonn)

Recently, several research groups demonstrated that in native photosynthetic systems there exist molecules remaining an entangled state even at room temperature. We have also demonstrated that a correlated radical pair in a pure singlet state, which is generated by light-induced electron-transfer reactions in the primary energy conversion steps of photosynthesis, has a relatively long coherence at room temperature. Quantum coherence in the correlated spin pair can be manifested as quantum beats by high time-resolution EPR. In order to clarify how long-lived quantum coherence is attained in the biological environment composed of thermally fluctuating water and amino acids, high time-resolution EPR have been applied to a correlated spin pair (entangled state) in this work. There exist two different electron-transfer pathways in each protein, two spin pairs composed of the same molecules are generated on each the pathway. In our measurements, firstly, one of the spin pairs was investigated by EPR. It was shown that the coherence time is mainly influenced by surrounding nuclear spins, and coherence time was prolonged up to 1.2 ms from 600 ns at 100K by performing deuteration and ^{15}N-substitution. Compared to the coherence times, however, those of the other spin pair were half, thought the two spin pairs locate under the similar chemical circumstance. No magnetic field dependences were observed for the quantum coherence time of the spin pair by Q-band（34GHz, 1.2T）and W-band（94GHz, 3.4T）EPR measurements. Further experiments are in progress for proteins under the modified chemical circumstances.

Proposed research 08: <u>Research for electrical control of quantum information by NV center in diamond</u>

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

In this project, we investigate the single nitrogen vacancy (NV) center in diamond. By using the confocal microscopy combined with magnetic resonance system, the single spins can be controlled and optically detected at room temperature. Recently, the optical, chemical and electrical control of its charge state of NV center has been investigated because the control is essential for the stability and manipulation of the qubit. However, electrical manipulation of the charge state of a single NV^- centre and its dynamics have not yet been reported. Recently, we realized the electrical manipulation of the charge state of a single NV^-. Furthermore, we investigate the dynamics by time-resolved measurements and single-shot measurement. By using the single-shot measurement technique, we experimentally demonstrate for the first time deterministic, purely electrical charge state manipulation of individual NV centers. Our results pave the way not only for ultrafast electrical control of qubits, long T_2 quantum memory, and quantum sensors associated with single NV centers but also for classical memory devices based on single atomic storage bits working under ambient conditions.

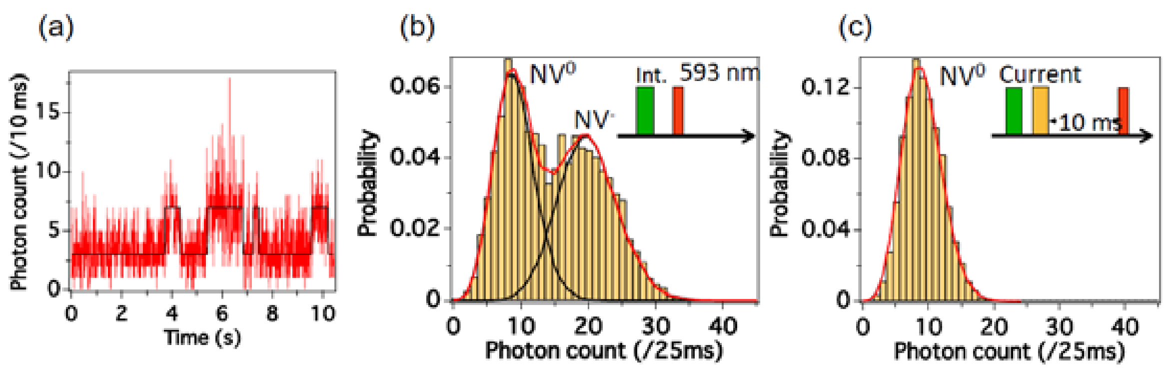


Figure (a) Time trace of the fluorescence of a single NV under continuous illumination with 593 nm laser light, showing abrupt jumps between two distinct states of the NV one with high (NV^-) and one with low count rates (NV^0). (b) Histogram of photon counts during the 593 nm measurement pulse after illuminating the NV with 532 nm. The solid lines are obtained from fitting the sum of two Poisson distributions. (c) Histogram of photon counts during the 593 nm measurement pulse, after illuminating the NV with 532 nm and current injection.