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

Research topic: 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 Nanoelectronics Laboratory)

—Large dispersive shift in superconducting flux qubit

We study dispersive readout in superconducting flux qubits. Our system consists of a flux qubit capacitively coupled to a superconducting transmission line cavity with ~ 10 GHz resonant frequency. In order to discriminate the state of the qubit precisely, it is desirable that the magnitude of the dispersive shift ▪ is large. For the two-level system, ▪ is given by $g^2/$▪ where g is the coupling strength and ▪ is the detuning between the qubit and the cavity. For the multilevel system such as superconducting qubits, however, this formula is modified due to the contributions from higher levels [1]. It has been pointed out that if the cavity resonant frequency lies between f_{01} and f_{12} transition frequencies of the qubit, the magnitude of ▪ becomes large because of the constructive contributions from different levels [1]. Our flux qubit has f_{01}~5 GHz and f_{12}~15 GHz at the optimal flux bias, thus satisfying this condition. Moreover, because of the large anharmonicity (f_{12} - f_{01}) of the flux qubit, we can easily make g as large as ~100 MHz, while staying in the deep dispersive limit, which is not the case for transmon or phase qubit with much smaller anharmonicity. Both of these enhance the magnitude of ▪ and we have obtained the dispersive shift as large as 80 MHz, which agrees well with the prediction by the energy band calculation.

[1] J. Koch et al., PRA 76, 042319 (2007)

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)

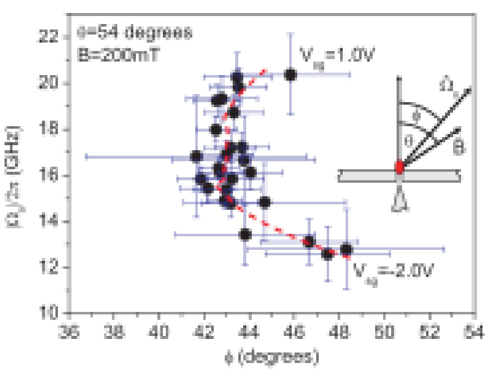
We have precisely evaluated Lande g-tensor of an InAs quantum dot by measuring the differential conductance of the tunneling current between the source and drain contacts. Then we found that the g-tensor can be largely controlled by the voltage applied to the sidegate. This result suggests that the g-tensor magneto resonance (g-TMR) of a single spin is possible, while g-TMR had only been reported for the ensemble spins in a quantum well. (Fig.Left)[1]

By attaching leads with strikingly different dimensionality (2D and 3D) to a GaAs vertical quantum dot, we observed for the first time strong current blocking for one of the bias polarity, which can be explained by the geometric configurations.[2] We also made a laterally coupled vertical quantum dot and observed an oscillating current as a function of the magnetic field applied in-plane. The phase of this Aharonov-Bohm oscillation changes with the gate voltage, which is successfully explained with our theoretical model. (Fig.Right)) [3]

[1] R. S. Deacon, Y. Kanai, S. Takahashi, A. Oiwa, K. Yoshida, K. Shibata, K. Hirakawa, Y. Tokura and S. Tarucha, Phys. Rev. B 84, 041302(R) (2011).

[2] K. Yamada, M. Stopa, T. Hatano, T. Yamaguchi, T. Ota, Y. Tokura and S. Tarucha, Phys. Rev. B 84, 201303(R) (2011).

[3] T. Hatano, T. Kubo, Y. Tokura, S. Amaha, S. Teraoka, and S. Tarucha, Phys. Rev. Lett. 106, 076801 (2011).



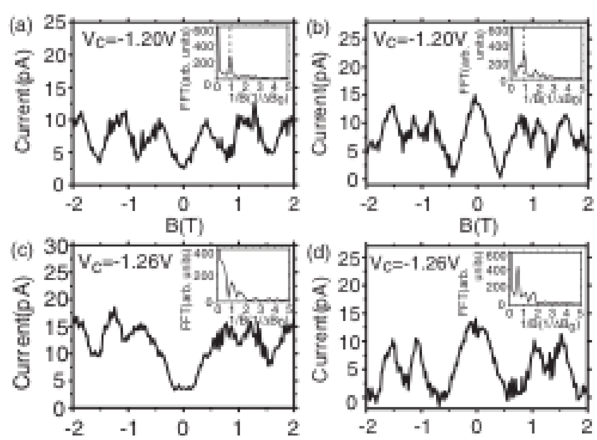


Fig.(Left) Sidegate voltage dependence of the angle and the amplitude of the g-TMR nutation frequency (Ω_0) for a fixed amplitude and angle of the external magnetic field.

Fig.(Right) In-plane field dependence of the current through a laterally coupled vertical quantum dot. Total number of electrons is one and left/right column represents bonding/anti-bonding orbital and the upper/lower array is for the center gate voltage of -1.20V/-1.26V.

Research topic: Molecular spin quantum cybernetics
Proposed research B01: <u>Molecular spin quantum control</u>
Project Leader: Masahiro Kitagawa (Professor, Graduate School of Engineering Science, Osaka University)

—**Noiseless Quantum Amplification**

Amplification is one of the most significant functions in classical cybernetics. However the quantum counter part is not straightforward due to uncertainty principle or no-cloning theorem. Our recent experimental demonstration of scalable spin amplification in broad sense will be elevated to true spin amplification by repeating QND measurement of z component of the input spin with CNOT gates. We have clarified the general notion of spin amplification by comparison with quantum amplifications of photon as shown in the Table below. First, the spin amplification we are currently working on corresponds to photon amplification proposed by Yuen and yet to be realized rather than Laser (practical amplifier for light) or degenerate parametric amplifier (noiseless quantum amplifier for I or Q component of light). From the Table, it is found that "spin squeezing" which corresponds to degenerate parametric amplification can be another kind of noiseless spin amplification. Existence of isotropic spin amplification is also predicted although it will not be noiseless and physical realization is yet to be found. We will investigate the possibility of these new kinds of spin amplifications as well.

Photon (Boson)	Spin
Noiseless Quantum Amplification	
Photon Number Amplification Amplify photon number N, Erase phase ▪	Spin Amplification Amplify Sz, Erase Sx and Sy
Degenerate Parametric Amplification (squeezing) Amplify I component a_1, Attenuate Q comonent a_2	Spin Squeezing Amplify S_x, Attenuate S_y
Isotropic Quantum Amplification (with inevitable quantum noise)	
Laser, Non-degenerate Parametric Amplification Amplify a_1 and a_2	Isotropic Spin Amplification Amplify Sx, Sy, Sz

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, it is important to realize a single site addressing and detection. We have successfully made progress towards this goal. First, we successfully created the ytterbium Bose-Einstein condensate in a thin glass cell region, with the severe limitation on optical access due to the large objective lens set quite close to the cell surface. Furthermore, we created strongly anisotropic trap with a very tight confinement along one direction by interference between two laser beams, and successfully load the created ytterbium Bose-Einstein condensate into the anisotropic trap, which was confirmed by strongly anisotropic time-of-flight image. In addition, we applied the two dimensional optical lattice with the lattice constant of 266 nm to the pancake-shaped two-dimensional condensate. Also, we actually set an objective lens with high-NA just above the thin glass cell, and successfully took an absorption image. We also developed a new method for single site manipulation, light-shift addressing combined with a ultranarrow optical transition.

In the quantum simulation using cold atoms in an optical lattice, we successfully realized an optical super-lattice which can simulate various interesting lattice configurations, using frequency controlled 532 nm and 1064 nm laser light. Experimentally, first we created a superfluid state in a relatively shallow optical super-lattice depth, and confirmed the appearance of new interference peaks in the matter wave interference image in the time-of-flight configuration only with the simultaneous application of 1064nm and 532 nm.

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 multi-segmented planar trap and performed transportation of Ca^+ ions between different trapping regions. This technique enables us to control a large number of ions in scalable quantum information processing. We numerically calculated the appropriate control dc voltages so that we maintain the curvature of trapping potential during transportation. According to the calculation, we applied the control voltages and succeeded transportation of ions without any loss. Figure 1 shows the images obtained when the ions are trapped 200 μm above the surface and moved along the *z* direction by 1 mm.

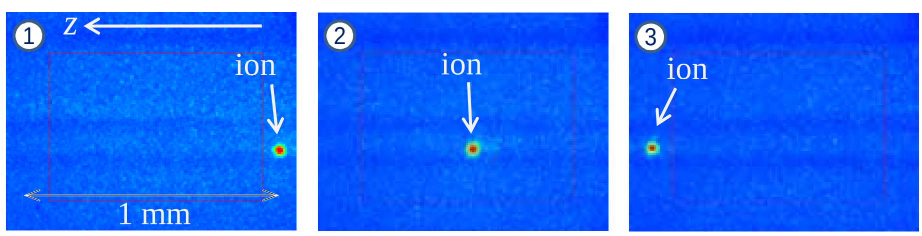


Fig 1

Optical transitions have been mainly used for generation of entangled states in trapped-ion systems so far. Although very recently there have been reports demonstrating direct generation of entanglement in RF/microwave transitions, such experiments require special conditions such as spatially inhomogeous oscillating fields or large magnetic-field gradients. We have recently proposed and demonstrated a method to directly generate entanglement in an RF transition with the help of entangling operation based on optical spin-dependent forces. Using this method, we have generated an entangle state in an RF transition between the ground-state Zeeman sublevels of $^{40}Ca^+$ with fidelity 0.68. In addition, we have showed that the generated state is a decoherence-free state, i.e. a state that is robust against certain types of noises from environments. We have shown that the generated entangled state has a coherence-decay time of 200ms, which is by more than 1 order larger than the case of one ion.

Research topic: Optical system quantum cybernetics

Proposed research D01: <u>Realization of quantum cybernetics using photonic Quantum circuits</u>

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

―Highly Efficient Coupling of Photons from Nanoemitters into Single-Mode Optical Fibers

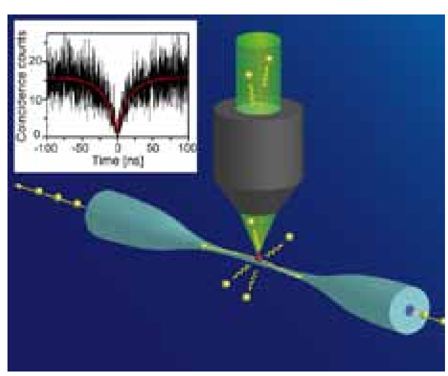
Photons have excellent controllability and are easily interfaced with naturally occurring atoms and molecules as well as artificial atoms. Our planning team aims to control photonic quantum state and explore new concepts in terms of quantum cybernetics. We also aim to achieve quantum state control between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

Collection of fluorescence photons from single nanoemitters is of fundamental importance in quantum information science. Single nanoemitters such as quantum dots (QDs) can be employed as single-photon sources that are crucial devices for realizing quantum cryptography in future secure communication networks.

Conventionally, the fluorescence photons from nanoemitters are collected by high-NA objective lens that normally can collect 10% of total emitted photons. However, subsequent optical components such as lenses and single-mode fibers reduce the actual collection efficiency down to 1-2% of the total emission of single nanoemitters. Coupling the nanoemitter's fluorescence with single mode fiber is very important for the fiber integration and development of future quantum photonic networks.

We have demonstrated highly efficient coupling of fluorescence from single QDs into single-mode fibers by using ultrathin tapered fibers. We succeeded in producing tapered fibers with a diameter of 300 nm and a transmittance of 90%. We preserved their transmittance by conducting all experiments in a dust-free environment. We were able to couple 7.4 % of the total emitted photons from single CdSe/ZnS nanocrystals into tapered fibers. This efficient photon collection technique is promising for single-photon sources.

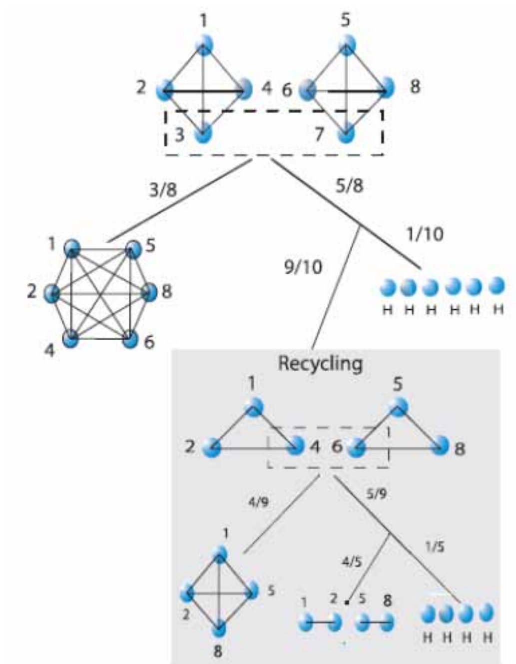
[1]M Fujiwara, K. Toubaru, T. Noda, H.-Q. Zhao, S. Takeuchi, Nano Lett. **11**, 4362-4365 (2011).



Coupling of single nanoemitters to single mode optical fiber using 300-nm ultrathin tapered fibers

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

Project Leader: Masato Koashi (Professor, Photon Science Center of the University of Tokyo)



Multipartite entanglement is considered to be an important resource for realizing various tasks of quantum information. In creating entanglement among many particles, a straightforward way of adding particles one by one to increase the size of entanglement is not necessarily efficient, especially when each adding step only succeeds probabilistically. A better strategy is to fuse two groups of already entangled particles together to double its size. Here we proposed a simple fusion scheme for W states of photonic qubits and analyzed its efficiency. W states are renowned for their strongest robustness against losses via the web-like structure of pair-wise entanglement, but extending such a structure is inherently probabilistic and the resource consumption becomes exponential in the 'one-by-one' extension schemes. We calculated the optimal efficiency of our new fusion scheme and found that the resource consumption scales sub-exponentially. We further showed that the efficiency can be further improved by introducing recycling of the resources.

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)

In collaboration with Takeuchi group (Hokkaido/Osaka University), we are demonstrating experimentally the strong consistency and asymptotic efficiency in an adaptive quantum estimation (AQE) scheme (J. Phys. A: Math. Gen., **39** (2006) 12489). In the previous News Letter, we pointed out the existence of systematic errors in the experiment. Later, we have got rid of systematic errors, and have succeeded in the first experimental demonstration of AQE. The angle of a half wave plate (HWP) that initializes the linear polarization of input photons was estimated using AQE. A sequence of AQE was carried out with $n = 300$ input photons, and the sequence was repeated $r = 500$ times for four different settings of HWP. A series of statistical analyses for these results concluded the following: 1) the χ 2-test showed that the distribution of the estimated values had converged quite well to a normal distribution at $n = 300$, 2) the interval estimation for the mean and variance showed that the estimated values were in excellent agreement with the theoretical values.

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)

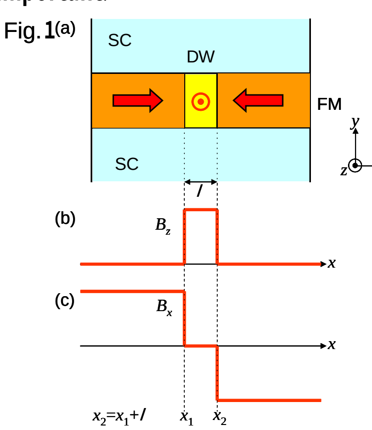
We have studied a quantum state generated by coupling between electron's spin and the phase degree of freedom of superconducting (SC) order parameter, with a view to an application to precise measurement for electromagnetic properties. The conventional Josephson junction defines the voltage standard around the world. Furthermore, together with the resistance standard defined by the quantum Hall effect, the Josephson junction strongly contributes to the electromagnetic standard in a dc regime. It goes without saying that the precise measurements are indispensable for science and technology.

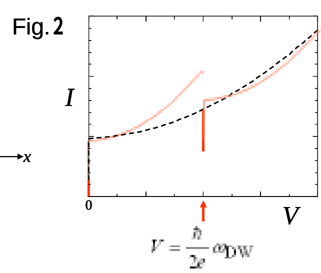
On the other hand, it is proposed that the magnetic domain wall (DW) in the ferromagnet can be applicable to some devices such as the non-volatile memory[1]. However, the DW motion driven by current or magnetic filed is quite complicated, and must be measured precisely by some experimental techniques. So far, we have studied the current-voltage (I-V) curve in the ferromagnetic Josephson junction, in which the two SC electrodes are separated by the ferromagnet with DW (see Fig. 1(a))[2]. By assuming the magnetic flux as shown in Figs.1 (b) and (c), and by supposing the gauge invariant phase, the Josephson current ($I_J(t)$) is given by,

$$I_J(t) = I_c \frac{\sin(\pi\phi_x)}{\pi\phi_x}\left\{ \sin(\varphi_0 - \pi\phi_z\lambda)\left(x_1 + \frac{1}{2}\right) + \sin(\varphi_0 + \pi\phi_z\lambda)\left(\frac{1}{2} - x_2\right)\right\} + \lambda I_c \frac{\sin(\pi\phi_z\lambda)}{\pi\phi_z\lambda}\sin\varphi_0$$

where ϕ_x (ϕ_z) denotes the x-(z-)component of the magnetic flux. By this equation, one can expect that the harmonic oscillation of DW with a fixed width (λ) will lead to the stepwise structure of I-V curve as shown in Fig. 2. The voltage, at which the step appears, can be assigned by the DW frequency (ω_{DW}) and the fundamental constants. Therefore, our results can be a new principle for the precise measurement of DW motion.

In the "quantum cybernetics" project, the coherent quantum phase slip effect, which is a phenomenon involving coherent tunneling of quantum magnetic flux through a thin SC wire, is studied with an eye to the quantum current standard. It is conjugate to the conventional Josephson effect and the quantum voltage standard. Since the quantum magnetic flux is considered to be the smallest limit of DW, we are now trying to develop our theory to a small junction, in which the charging effect becomes more important.





[1] S. Parkin et al. Science 320, 190 (2008).

[2] S. Hikino, M. Mori, W. Koshibae, and S. Maekawa, arXiv:1202.0382.

[3] J.-S. Tsai, News Letter Vol. 5. p.2 (2011)

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 develop the single nitrogen vacancy (NV) center in diamond. By using the confocal microscopy combined with magnetic resonance system, we can control and optically detect the single spins. So, it is expected as good quantum bit system. In addition, due to their outstanding photostability at room temperature, single defects in diamond and in particular single NV center have been used as single photon source for quantum cryptography and single photon interference by laser excitation. The development of such a promising solid-state sources of single photons is a major challenge in the context of quantum communication, optical quantum information processing, and metrology. Recently, we have demonstrated electrically driven single photon emission by using single NV center in diamond at room temperature. Our results prove that functional single defects can be integrated into electronic control structures, which is a crucial step towards elaborated quantum information devices.

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)

—Singlet spin blockade and nuclear spin entanglement

Polarized10^5 nuclear spins in GaAs quantum dots have a long coherence time. Coding upward/downward polarization as 1 qubit, initialization, rotation, and measurement are already demonstrated. So, if we can entangle the nuclear spin polarizations in one dot to that of another dot, nuclear polarization qubits will meet the DiVincenzo's criteria.

In the spin blockade state of double quantum dot, two-electron spin state is fixed to be one of the triplet *T* (*T*+, *T*0, *T*-), and the leakage current flow if it is scattered to be a singlet *S*. The spin state is always subject to a strong projective measurement whether it is *S* or *T*. Thus to consider the spin flip-flops between electron and nuclei under such "*S* or *T*" measurement, it is useful to regard the process as swapping of *electron spin pair* (*S*, *T*+, *T*0, *T*-) and *nuclear spin pair* (*s*, *t*+, *t*0, *t*-). Because the electron spins are nearly localized on each dot, the nuclear spin pair is made of a nuclear spin in one dot and another nuclear spin in the other dot. In case of *T*+→*S* electron spin scatterings with accompanying the nuclear spin flopps, once after the electron spins are "measured to be *S*", one of the *s* nuclear spin pair is now becomes to *t*+ (*T*+Ä*s*® *S*Ä*t*+). By repeating the *T*+→*S* scatterings and the measurement to find out the electron spin pair to be *S*, numbers of *t*+ nuclear spin pairs will increase, and eventually nuclear spins in both of the dots are polarized to the same direction.

On the other hands, if we can increase a number of *s* nuclear spin pairs, a non-local (inter-dot) entanglement of nuclear spins can be created. A singlet spin blockade, *i.e.*, two-electron spin state is fixed to be singlet *S*, and the leakage current flow if it is scattered to one of the triplet *T* (*T*+, *T*0, *T*-), is a necessary tool. Currently we are searching for such a singlet spin blockade.