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科研費
KAKENHI

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研究課題名（和文）超伝導ハイブリッドシステムの量子物理学

研究課題名（英文）Quantum physics of superconducting hybrid systems

研究代表者
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研究成果の概要（和文）：当グループの基盤Aプロジェクトは非常に成功を収め、その研究課題に関して、トップの物理学ジャーナルにおいて数多くの論文が出版された。研究成果であるこれらの論文リストは研究成果報告内容ファイルに記載されている通りである。Web of Scienceによると、論文の重要な結果のいくつかは多数引用されており、 さらに、PIは、2017年に日本において選ばれた唯一の外国人の物理学者として選ばれ、高く評価されている。

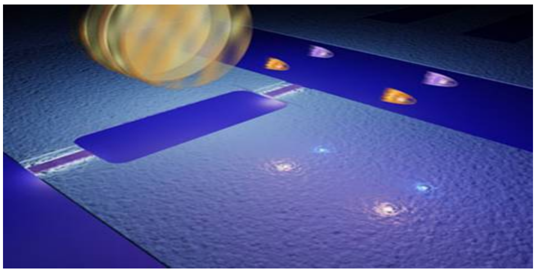
研究成果の概要（英文）：Our finalized Kiban-A proposal was extremely successful, generating many publications in top physics journals. These are listed in our web site, as well as in this report. Several of these important results are highly cited, according to the Web of Science. Moreover, the PI is the only foreign physicist in all of Japan to be highly cited in 2017.

研究分野：理論物理学

キーワード：quantum physics　superconducting qubits　hybrid systems

１．研究開始当初の背景 【Initial Background of the Research】

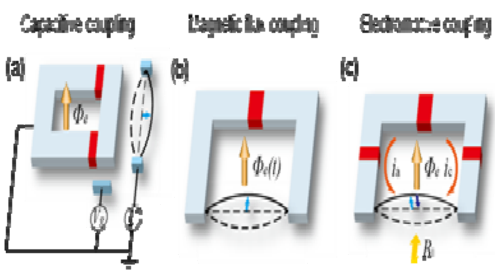
Superconducting (SC) quantum circuits can act as artificial atoms made from electrical circuit elements. At very low temperatures, these circuits have quantized energy levels. Transitions between levels are induced by applying pulsed microwave electromagnetic radiation to the circuit, revealing quantum coherent phenomena analogous to (and in certain cases beyond) those observed with coherent atomic systems. SC quantum nano-devices have been attracting growing interest worldwide and are being extensively studied (especially in the EU & USA) for both basic science and future applications. These new types of SC quantum circuits are very promising, because these can be integrated into a chip with controllable macroscopic quantum properties. Additional background on our research can be found in our recent papers in Science (2009, 2014), Nature (two in 2011), Nat. Phys. (2013, 2014), Physics Reports (2010, 2 in 2011, 12, 2 in 15, 16, 3 in 2017), Rep. Progr. Phys. (2011, 2014), and Rev. Mod. Phys. (2009, 12, 13, 2014).



２．研究の目的　【Research Objectives】

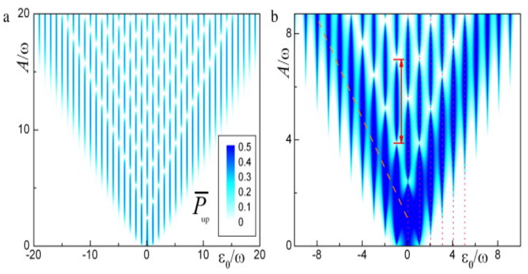
The main purpose of this proposal is to study (superconducting and semiconducting) quantum devices as “Artifical Atoms”, and elucidate how these “giant atoms” interact with light, transmission lines, (electro-magnetic or mechanical) resonators, and to use the gained knowledge for designing on-chip hybrid quantum processors, quantum controllers and quantum sensors. We will do this through theoretical and computational methods and in close collaboration with experimentalists in Japan, US and Europe. We will apply the techniques developed in our group for artificial atoms made of superconducting (SC) qubits to semi-conducting devices. We will test the developed models and the performance of designed quantum devices through our existing collaborations with ten experimental groups with whom we have already published together. We will also continue investigating electron vortex beams and other related topics at the interface with optics, which we pioneered in our group (PRL 2007, 2011, PRX 2012) and contributed to experimental realizations (PRL 2013, Nat. Phys. 2013, Nature Comm. 2014).

Hybrid circuitsbring together two or more physical systems (atoms, spins, SC systems, optomechanics and nanoelectromechanical systems, etc) to obtain unprecedented performance and features that cannot be attained with only one of the systems. These are considered indispensable for future quantum technologies (e.g., quantum sensors and detectors, quantum controllers, etc), because hybrid circuits aim at taking the best features (green text below, left) and avoid the problematic aspects (red text below) of the constituent physical (macro and micro) systems. The schematic diagram below (left) shows a hybrid quantum processor coupled to a memory unit via either a quantum data bus or “bridge” (indirect coupling) or via direct coupling. For fast operations, SC circuits can serve as the processor; for long coherence times, atomic (or spin) systems can play the role of the memory in a hybrid quantum system. In the direct-coupling case, SC qubits couple with atoms (or spins) via electromagnetic fields. In the indirect-coupling case, a high-fidelity quantum resonator (e.g., coplanar waveguide resonator) acts as a data bus to transfer (quantum) information between the two components of the hybrid quantum system. Our research group has found and studied many links between SC physics, AMO (Atomic-Molecular-Optics) physics, CM (Condensed matter), and nano-science. The goal of this proposal is to continue and significantly expand these very fruitful studies, in close collaboration with many scientists, and to use them for designing novel quantum circuits.



３．研究の方法 【Research Method】

We have extensively studied a large variety of artificial atoms and uncovered many connections between AMO physics, CM, nano-science, and quantum information Processing (QIP), as well as performed pioneering research in optics and electron beams. The results of our interdisciplinary studies have been well received. The purpose of this proposal is to continue and significantly expand these fruitful studies, in close collaboration with many scientists. We will model and evaluate the characteristics of engineered quantum devices, such as superconducting circuits, nanomechanical systems, semiconducting quantum dots, etc., and integrate them for building hybrid quantum circuits that will facilitiate quantum processors, simulators and controllers. To do this, a large number of components and possible quantum states generally have to be accounted for. This makes computational methods extremely important in this field of physics, and we will continue our previous works on developing theoretical and computational methods that make it possible to model experimentally-relevant novel devices, and explore new physics. In this research we will develop our computational methods to a new level where the analysis is done both at the single device and the system level. The latter is very challenging and expected to lead to new features and interesting physics.



４．研究成果 【Research results】

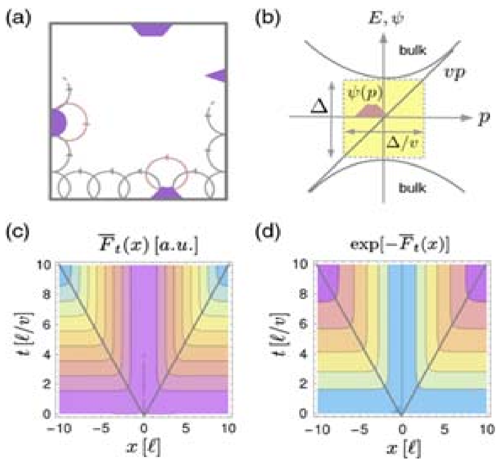
Below please find a summary of a small subset of our many results. Others are not listed below, due to space limitations.

#1 "Microwave photonics with superconducting quantum circuits"

The emerging field of superconducting quantum microwave circuits has been driven by many new interesting phenomena in microwave photonics and quantum information processing. For instance, the interaction between superconducting quantum circuits and single microwave photons can reach the regimes of strong, ultra-strong, and even deep-strong coupling. Many higher-order effects, unusual and less familiar in traditional cavity quantum electrodynamics with natural atoms, have been experimentally observed, e.g., giant Kerr effects, multi-photon processes, and single-atom induced bistability of microwave photons. These developments may lead to improved understanding of the counterintuitive properties of quantum mechanics, and speed up applications ranging from microwave photonics to superconducting quantum information processing. In this article, we review experimental and theoretical progress in microwave photonics with superconducting quantum circuits. We hope that this global review can provide a useful roadmap for this rapidly developing field.

#2 "Disorder-Induced Dephasing in Backscattering-Free Quantum Transport"

We analyze the disorder-perturbed transport of quantum states in the absence of backscattering. This comprises, for instance, the propagation of edge-mode wave packets in topological insulators, or the propagation of photons in inhomogeneous media. We quantify the disorder-induced dephasing, which we show to be bound. Moreover, we identify a gap condition to remain in the backscattering-free regime despite disorder-induced momentum broadening. Our analysis comprises the full disorder-averaged quantum state, on the level of both populations and coherences, appreciating states as potential carriers of quantum information.

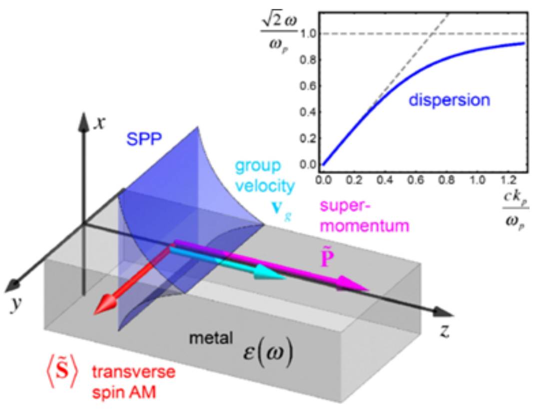


#3 "Hole Spin Resonance and Spin-Orbit Coupling in a Silicon Metal-Oxide-Semiconductor Field-Effect Transistor"

We studied hole spin resonance in a p-channel silicon etal-oxide-semiconductor field-effect transistor. In the subthreshold region, the measured source-drain current reveals a double dot in the channel. The observed spin resonance spectra agree with a model of strongly coupled two-spin states in the presence of a spin-orbit-induced anticrossing. Detailed spectroscopy at the anticrossing shows a suppressed spin resonance signal due to spin-orbit-induced quantum state mixing. This suppression is also observed for multiphoton spin resonances. Our experimental observations agree with theoretical calculations.

#4 "Optical Momentum, Spin, and Angular Momentum in Dispersive Media"

We examined the momentum, spin, and orbital angular momentum of structured monochromatic optical fields in dispersive inhomogeneous isotropic media. There are two bifurcations in this general problem: the Abraham-Minkowski dilemma and the kinetic (Poynting-like) versus canonical (spin-orbital) pictures. We show that the kinetic Abraham momentum describes the energy flux and group velocity of the wave in the medium. At the same time, we introduce novel canonical Minkowski-type momentum, spin, and orbital angular momentum densities of the field. These quantities exhibit fairly natural forms, analogous to the Brillouin energy density, as well as multiple advantages as compared with previously considered formalisms. As an example, we apply this general theory to inhomogeneous surface plasmon-polariton (SPP) waves at a metal-vacuum interface and show that SPPs carry a "supermomentum,".



5."Amplified Optomechanical Transduction of Virtual Radiation Pressure"

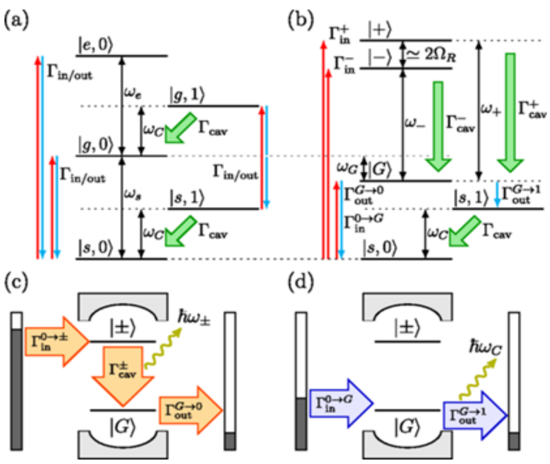
We described how, utilizing a time-dependent optomechanical interaction, a mechanical probe can provide an amplified measurement of the virtual photons dressing the quantum ground state of an ultrastrongly coupled light-matter system. We calculated the thermal noise tolerated by this measurement scheme and discuss an experimental setup in which it could be realized.

#6 "Hybrid Quantum Device with Nitrogen-Vacancy Centers in Diamond Coupled to Carbon Nanotubes"

We showed that nitrogen-vacancy (NV) centers in diamond interfaced with a suspended carbon nanotube carrying a dc current can facilitate a spin-nano-mechanical hybrid device. We demonstrated that strong magneto-mechanical interactions between a single NV spin and the vibrational mode of the suspended nanotube can be engineered and dynamically tuned by external control over the system parameters. This spin-nano-mechanical setup with strong, intrinsic, and tunable magnetomechanical couplings allows for the construction of hybrid quantum devices with NV centers and carbon-based nanostructures, as well as phonon-mediated quantum information processing with spin qubits.

#7 "Ground State Electroluminescence"

Electroluminescence, the emission of light in the presence of an electric current, provides information on the allowed electronic transitions of a given system. It is commonly used to investigate the physics of strongly coupled light-matter systems, whose eigenfrequencies are split by the strong coupling with the photonic field of a cavity. Here we showed that, together with the usual electroluminescence, systems in the ultrastrong light-matter coupling regime emit a uniquely quantum radiation when a flow of current is driven through them. While standard electro-luminescence relies on the population of excited states followed by spontaneous emission, the process we describe herein extracts bound photons from the dressed ground state and it has peculiar features that unequivocally distinguish it from usual electroluminescence.

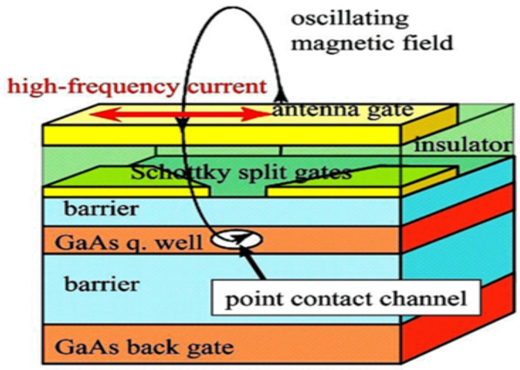


#8 "Bistable Photon Emission from a Solid-State Single-Atom Laser"

We predicted a bistability in the photon emission from a solid-state single-atom laser comprising a microwave cavity coupled to a voltage-biased double quantum dot. To demonstrate that the single-atom laser is bistable, we evaluated the photon emission statistics and show that the distribution takes the shape of a tilted ellipse. The switching rates of the bistability can be extracted from the electrical current and the shot noise in the quantum dots. This provides a means to control the photon emission statistics by modulating the electronic transport in the quantum dots. Our prediction is robust against moderate electronic decoherence and dephasing and is important for current efforts to realize single-atom lasers with gatedefined quantum dots as the gain medium.

#9 "Quantum state tomography of large nuclear spins in a semiconductor quantum well: Optimal robustness against errors as quantified by condition numbers"

We discussed methods of quantum state tomography for solid-state systems with a large nuclear spin I = 3/2 in nanometer-scale semiconductors devices based on a quantum well. Due to quadrupolar interactions, the Zeeman levels of these nuclear-spin devices become nonequidistant, forming a controllable four-level quantum system (known as quartit or ququart). The occupation of these levels can be selectively and coherently manipulated by multiphoton transitions using the techniques of nuclear magnetic resonance (NMR) [Yusa et al., Nature (London) 434, 1001 (2005)]. These methods are based on an unconventional approach to NMR, where the longitudinal magnetization Mz is directly measured. This is in contrast to the standard NMR experiments and tomographic methods, where the transverse magnetization Mxy is detected. The robustness against errors in the measured data is analyzed by using the condition number based on the spectral norm. We propose several methods with optimized sets of rotations yielding the highest robustness against errors, as described by the condition number equal to 1, assuming an ideal experimental detection. This robustness is only slightly deteriorated, as given by the condition number equal to 1.05, for a more realistic "noisy" Mz detection based on the standard cyclically ordered phase sequence (CYCLOPS) method.



#10 "Quantum spin Hall effect of light"

Maxwell's equations, formulated 150 years ago, ultimately describe properties of light, from classical electromagnetism to quantum and relativistic aspects. The latter ones result in remarkable geometric and topological phenomena related to the spin-1 massless nature of photons. By analyzing fundamental spin properties of Maxwell waves, we show that free-space light exhibits an intrinsic quantum spin Hall effect—surface modes with strong spin-momentum locking. These modes are evanescent waves that form, for example, surface plasmon-polaritons at vacuum-metal interfaces. Our findings illuminate the unusual transverse spin in evanescent waves and explain recent experiments that have demonstrated the transverse spin direction locking in the excitation of surface optical modes. This deepens our understanding of Maxwell's theory, reveals analogies with topological insulators for electrons, and offers applications for robust spin-directional optical interfaces.

５．主な発表論文等（すべて査読有）

Only a few selected papers on this project:

1. X. Gu, A.F. Kockum, A. Miranowicz, Y.X. Liu, F. Nori, *Microwave photonics with superconducting quantum circuits,* Physics Reports **718-719**, pp. 1-102 (2017).

2. C. Gneiting, F. Nori, *Disorder-induced dephasing in backscattering-free quantum transport,* Phys. Rev. Lett. **119**, 176802 (2017).

3. K. Ono, G. Giavaras, T. Tanamoto, T. Ohguro, X. Hu, F. Nori, *Hole spin resonance and spin-orbit coupling in a silicon metal-oxide-semiconductor field-effect transistor* Phys. Rev. Lett. **119**, 156802 (2017).

4. K.Y. Bliokh, A.Y. Bekshaev, F. Nori, *Optical Momentum, Spin, and Angular Momentum in Dispersive Media* Phys. Rev. Lett. **119**, 073901 (2017).

5. M. Cirio, K. Debnath, N. Lambert, F. Nori, *Amplified Optomechanical Transduction of Virtual Radiation Pressure* Phys. Rev. Lett. **119**, 053601 (2017).

6. P.B. Li, Z.L. Xiang, P. Rabl, F. Nori, *Hybrid Quantum Device with Nitrogen-Vacancy Centers in Diamond Coupled to Carbon Nanotubes*, Phys. Rev. Lett. **117**, 015502 (2016).

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

8. N. Lambert, F. Nori, C. Flindt, *Bistable Photon Emission from a Solid-State Single-Atom Laser* Phys. Rev. Lett. **115**, 216803 (2015).

9. A. Miranowicz, S.K. Ozdemir, J. Bajer, G. Yusa, N. Imoto, Y. Hirayama, F. Nori, *Quantum state tomography of large nuclear spins in a semiconductor quantum well: Optimal robustness against errors as quantified by condition numbers,* Phys. Rev. B **92**, 075312 (2015).

10. K.Y. Bliokh, D. Smirnova, F. Nori, *Quantum spin Hall effect of light,* Science **348**, 1448-1451 (2015).

〔雑誌論文〕（計 124 件　すべて査読有）
〔学会発表〕（計　27 件）
〔その他〕URL: https://dml.riken.jp/

受賞リスト(Franco Nori)：

1. Dr. Franco Nori has been selected as a "Highly Cited Researcher", based on data from the Web of Science. The only foreign physicist in all of Japan in 2017. This because, during the last decade, his research group produced many (~ 33) highly cited papers (top 1% cited papers among all publications in all areas of physics).

2. Dr. Nori has been Elected Member of the Latin American Academy of Sciences. (2017)

3. Dr. Nori was elected as a Foreign Member of the Swedish Royal Society of Arts and Sciences in Goteburg, Sweden. (2017)

4. Dr. Nori was awarded as outstanding referee by the IOP (UK's Institute of Physics) (2017)

5. Dr. Nori was awarded by OSA (Optical Society of America) Publishing as an outstanding referee. (2017)

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