Theoretical Quantum Physics Laboratory
Chief Scientist: Franco Nori (Ph.D.)

(0) Research field
CPR Subcommittee: Physics
Keywords: nanoscience, quantum information, quantum circuits, quantum optics, interdisciplinary physics.

(1) Long-term goal of laboratory and research background

We perform interdisciplinary research at the interface between atomic physics, quantum optics, nano-science, quantum information, and computing. We also study theoretical condensed matter physics, computational physics, transport phenomena, as well as the dynamics of complex systems.

We are also studying optics, nanophotonics, artificial photosynthesis, light-to-electricity conversion, nano-mechanics, hybrid quantum electro-mechanical systems, quantum nano-electronics and quantum emulators. Particular emphasis is being placed on superconducting Josephson-junction qubits, scalable quantum circuitry and improved designs for their quantum control.

(2) Current research activities (FY2019) and plan (until Mar. 2025)

During this past fiscal year (April 2019 – March 2020) we obtained new results on: "Modelling the ultra-strongly coupled spin-boson model" (Nature Comm.); were able to resolve the long-standing problem of gauge ambiguities in ultrastrong-coupling cavity quantum electrodynamics (Nature Physics); studied quantum interferometry with a g-factor-tunable spin qubit (PRL); studied multi-electron ground state electroluminescence (PRL); we derived the "Klein-Gordon Representation of Acoustic Waves" and revealed the topological origin of surface acoustic modes (PRL); studied the acoustic radiation force and torque on small particles as measures of the canonical momentum and spin densities (PRL); studied the vanishing and revival of resonance Raman scattering" (PRL); topologically protected quantum coherence in a super-atom (PRL); N-phonon bundle emission via the Stokes process (PRL); shortcuts to adiabatic pumping in classical stochastic systems (PRL); and the large collective Lamb shift of two distant superconducting artificial atoms (PRL); as well as very popular paper on parity–time symmetry and exceptional points in photonics (Nature Materials). These among other results. In 2019, the PI was listed as a "Highly Cited Researcher" by Clarivate, based on Web of Science data. The only non-Japanese in Japan in the Physics category (11 in total for all of Japan in 2017, 8 total for 2018, and 7 in 2019). This because, during the last decade, his research group produced 42 highly cited publications (top 1% cited publications among all papers in all areas of physics).

Hybrid quantum systems

Hybrid quantum systems (HQS) bring together two or more physical systems (atoms, spins, superconducting systems, optomechanics and nanoelectromechanical systems, etc.) to obtain unprecedented performance and features that cannot be achieved with only one of the systems. These are considered to be important for future quantum technologies (e.g., quantum sensors and detectors, controllers, etc.), because hybrid circuits aim at taking the best features and avoid the problematic aspects of the constituent physical (macro and micro) systems. Cavity optomechanics is a rapidly developing field that couples light and mechanical modes to realize new types of HQSs which could be applicable for future information processing (e.g., switching or storage), in integrated photonic circuits. Moreover, optomechanical systems are promising for the study of fundamental quantum effects on a mesoscopic or macroscopic scale, like the dynamical Casimir effect: the generation of photons from the quantum vacuum due to rapid changes of the effective geometry (in particular, through changes in the electromagnetic boundaries), or material properties of electrically-neutral macroscopic or mesoscopic objects.

During this 5-year plan, we will continue our studies on quantum hybrid systems, opto-mechanics and the ultra-strong coupling (USC) limit of light-matter interactions (i.e. the USC limit of cavity QED). We will also continue studying (superconducting and semiconducting) quantum devices as "artificial 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.

Novel studies in optics, photonics, nano-photonics, and *PT*-symmetry in physics.

During this 5-year plan, we will continue our investigations of the following problems (which were pioneered by our group): (1) anomalous transverse momentum and spin in evanescent optical fields; (2) novel optical forces and torques in evanescent optical fields. Interaction of optical fields with dipole chiral particles. New forces, torques, and absorption rates measuring unusual field characteristics; (3) PT-symmetry involving coupled resonators, both in optics and also using superconducting circuits; (4) the physics of exceptional points in optics and condensed matter physics; and (5) electron vortex beams. Our previous work has had an impact in these areas (e.g., ~15 highly cited papers) and has motivated numerous experiments. Our future work will also motivate additional experiments and some of it will be done interacting with various experimental groups.

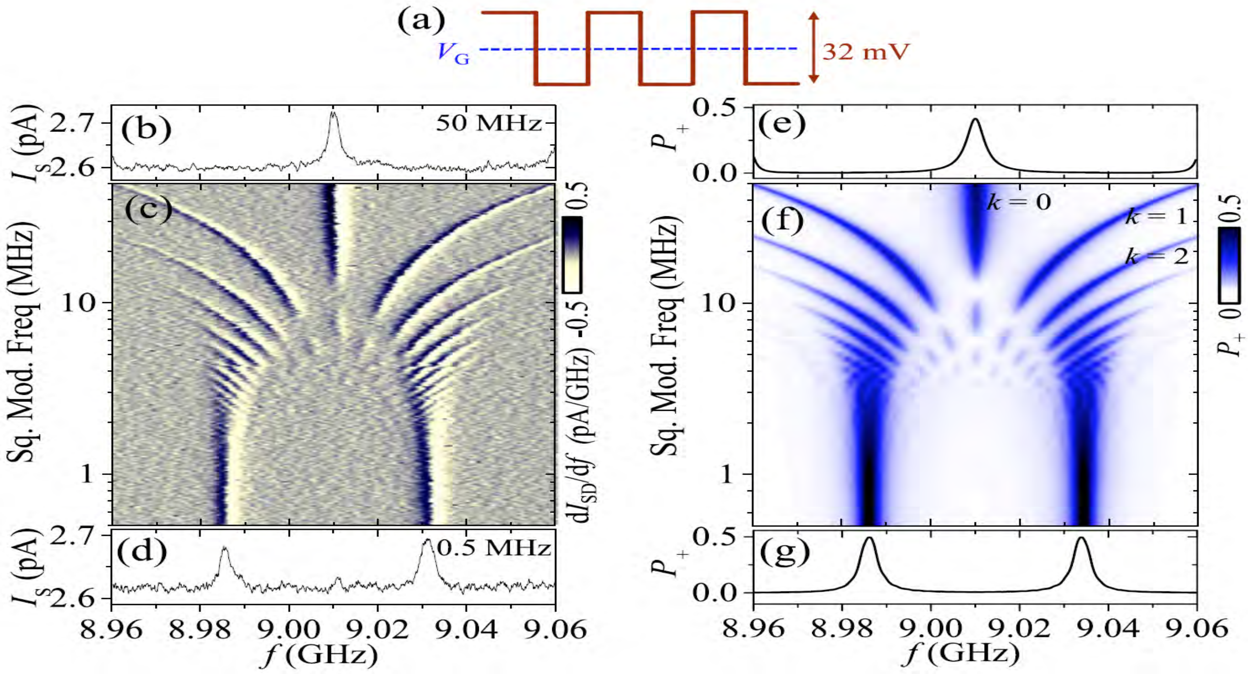

Figure 1: Quantum Interferometry with a g-factor-tunable spin qubit. We study quantum interference effects of a qubit whose energy levels are continuously modulated as in (a). Experimental data (b, c, d) compare well with our theoretical results (e, f, g), and demonstrate the potential of spin qubit interferometry implemented in a silicon device and operated at a relatively high temperature.

(3) Members as of March, 2020

(Chief Scientist)
Franco Nori

(Research Scientist)
Kostiantyn Bliokh, Neill Lambert,
Clemens Gneiting

(Postdoctral Researcher)
Luigi Garziano, Wei Qin,
Xin Wang, Vincenzo Macri,
Yanming Che, Wei Nie

(Contract Researcher)
Veaceslav Misco, Ravindra Chhajlany

(Visiting Researcher)
Yuran Zhang, Ken Funo, Tao Liu,
Yehong Chen

(Technical Staff)
Tarun Raheja

(Student Trainee)
Zhipeng Yang, Nobuyuki Yoshioka

(Intern)
Po-Chen Kuo, Alakesh Baishya,
Shreya Banerjee

(Assistant)
Ai Sato

(Part-time Worker)
Tomoki Sato, Noriko Ishida,
Kanako Tsukada, Ayako Carson

(4) Representative research achievements

1. N. Lambert, S. Ahmed, M. Cirio, F. Nori, *Modelling the ultra-strongly coupled spin-boson model,* Nature Communications **10**, 3721 (2019).
2. K.Y. Bliokh, F. Nori, *Klein-Gordon Representation of Acoustic Waves and Topological Origin of Surface Acoustic Modes,* Phys. Rev. Lett. **123**, 054301 (2019).
3. O. Di Stefano, A. Settineri, V. Macrì, L. Garziano, R. Stassi, S. Savasta, F. Nori *Resolution of gauge ambiguities in ultrastrong-coupling cavity quantum electrodynamics*
   Nature Physics **15**, pp. 803–808 (2019).
4. K. Ono, S.N. Shevchenko, T. Mori, S. Moriyama, F. Nori, *Quantum Interferometry with a g-Factor-Tunable Spin Qubit,* Phys. Rev. Lett. **122**, 207703 (2019).
5. M. Cirio, N. Shammah, N. Lambert, S. De Liberato, F. Nori, *Multielectron Ground State Electroluminescence,* Phys. Rev. Lett. **122**, 190403 (2019).

Laboratory Homepage
https://www.riken.jp/en/research/labs/chief/theor_qtm_phys/index.html