Virtual Photons in ultra-strong coupled systems

Abstracts

Quantum Nonlinear Optics without Real Photons

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Spontaneous parametric down-conversion is a well know process in quantum nonlinear optics in which a photon incident on a nonlinear crystal spontaneously splits in two photons. Here we propose an analogous physical process where one excited atom directly transfers its excitation to a couple of spatially separated atoms with probability approaching one. The interaction is mediated by the exchange of virtual rather than real photons. This nonlinear optical process is coherent and reversible, so that the couple of excited atoms can transfer back the excitation to the first one: the analogous for atoms of sum-frequency generation. The parameters used to investigate this process correspond to experimentally demonstrated values in circuit quantum electrodynamics systems. This approach can be expanded to consider other nonlinear inter-atomic processes as the four-qubit mixing and is an attractive architecture for the realization of quantum devices on a chip.

Deterministic quantum nonlinear optics with single atoms and virtual photons

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The regime of ultrastrong coupling (USC) between light and matter, where the coupling strength becomes comparable to the resonance frequencies of the photons and atoms, has been reached experimentally in various systems in the last few years. In this talk, we will show how such USC allows us to realize analogues of many nonlinear-optics phenomena in simple setups with one or more two-level atoms coupled to one or more resonator modes. The full quantum Rabi model, unlike the approximate Jaynes-Cummings model which is valid at lower coupling strengths, allows for processes that do not conserve the number of excitations in the system. For example, the standard scenario of a coherent Rabi oscillation, where a cavity and an atom exchange a single photon, can now be extended to multiphoton Rabi oscillations, which may provide an efficient route to constructing Fock states or entangled states of qubits [1]. In the same vein, a single photon can simultaneously excite two or more atoms [2]. Continuing along this line of research, we show that both single- and multiphoton frequency conversion processes can be realized with two resonator modes coupled ultrastrongly to a single two-level atom [3, 4]. Indeed, with this and similar setups we are able to provide a complete table with translations between three-wave and four-wave mixing processes in nonlinear optics and analogous realizations in USC systems [3]. Furthermore, we show that these setups also provide analogues for higher-harmonic and -subharmonic generation, multiphoton absorption, parametric amplification, and the Kerr and cross-Kerr effects [3]. We present a unified picture of how all these effects are realized via intermediate virtual states (connected by the counterrotating terms in the quantum Rabi model) and calculate the relevant transition rates.

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Superconducting qubit-oscillator circuit in the deep strong coupling regime

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Among a variety of cavity/circuit-QED systems, the superconducting flux qubit is a promising candidate for increasing the coupling strength further because of its huge magnetic moment. Using a flux qubit and a lumped-element resonator, instead of the widely used coplanar waveguide (CPW) resonators, we have achieved g/ω_r (g: coupling strength, ω_r: bare resonator frequency) comparable to or larger than 1 [1]. This regime is called the deep strong coupling regime, where a variety of interesting physics is expected [2]. In this presentation, the sample design and spectroscopy data will be shown. The spectra are well-described using a simple Hamiltonian in the Rabi model.

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Stimulated emission and reabsorption of virtual particles and multiphoton Rabi oscillations in ultrastrong cavity QED

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In quantum field theory, non-interacting (or bare) particles are dressed by a cloud of virtual particles to form physical particles. Most of the relevant properties of the physical particles are affected by these virtual particles, and it is only these modified properties that can be detected in experiments, not the properties of the bare particles. For this reason, even if the relations between the bare and the physical particles remain unobservable, the theoretical predictions must be expressed in terms of the properties of the physical particles, not of the bare particles. The influence of virtual particles features prominently in the USC and nonperturbative USC regimes of cavity quantum electrodynamics (QED), where the light-matter coupling rate becomes, respectively, comparable or larger than the unperturbed resonance frequencies of the system. While in the last years the USC regime has been reached experimentally in a variety of solid-state systems [1-3], only very recently the nonperturbative USC regime has been realized in a superconducting artificial atom tunably coupled to the electromagnetic continuum of a one-dimensional waveguide [4] or to an LC oscillator via Josephson junctions [5]. An interesting feature of these condensed-matter systems is that the effective interaction between atom-like transitions and the cavity field can be switched on and off by applying external control pulses, offering unprecedented possibilities for exploring quantum vacuum fluctuations and the relation between physical and bare particles [6]. Recently, it has been shown that in a single three level quantum system coupled to an optical resonator, the application of such external electromagnetic pulses can lead to the conversion of each virtual photon dressing a physical excitation into a physical observable photon, and back again. In this way, the hidden relationship between the bare and the physical excitations can be unravelled and becomes experimentally testable. The proposed scheme, which does not need ultrafast modulation of boundary conditions, can give rise to a conversion probability close to one. Moreover, this conversion between virtual and physical photons can be clearly pictured using Feynman diagrams with cut loops [7]. Another important feature of the USC regime is that the number of excitations in a cavity QED system is no longer conserved. Measurements on superconducting circuit QED systems in the USC regime have shown clear evidence of this feature: for example, coupling between states with a different number of excitations has been experimentally observed [1]. The coupling between these states, determining an anticrossing in the cavity transmission spectrum, originates from counterrotating terms in the light-matter interaction Hamiltonian that do not conserve the number of excitations. Indeed, the effects of these counterrotating terms become prominent only in the USC limit [8-9], while they can be safely neglected (RWA approximation) in the weak and strong coupling regimes. According to the Jaynes-Cummings model, the atom and the cavity mode can exchange a single excitation quantum through a coherent Rabi oscillation process. Such resonant quantum Rabi oscillations play a key role in the manipulation of atomic and field states for quantum information processing [10]. Recently, it has been shown that a system consisting of a single flux qubit ultrastrongly coupled to a coplanar-waveguide resonator can exhibit anomalous vacuum Rabi oscillations where two or three photons are jointly emitted by the qubit into the resonator and reabsorbed by the qubit in a reversible and coherent process [11]. Moreover, still increasing the coupling rate, a higher number of photons can be exchanged with the qubit during a single Rabi oscillation. The theoretical predictions show clear evidence for physics beyond the Jaynes-Cummings model and extend the concept of quantum Rabi oscillations. These anomalous Rabi oscillations can be exploited for the realization of efficient Fock-state sources of light and for the implementation of novel protocols for the control and manipulation of atomic and field states.

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Single-photon driven high-order sideband transitions in an ultrastrongly coupled circuit quantum electrodynamics system

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Ultrastrong coupling in circuit quantum electrodynamics systems not only provides a platform to study the quantum Rabi model, but it can also facilitate the implementation of quantum logic operations via high-lying resonator states. Here we report the experimental observation of high-order sideband transitions at the single-photon level in a quantum circuit system of a flux qubit ultrastrongly coupled to a coplanar waveguide resonator. With the coupling strength reaching 10% of the resonator's fundamental frequency, we obtain clear signatures of higher-order red- and first-order blue-sideband transitions, which have not been demonstrated experimentally elsewhere. These transitions are owing to the ultrastrong Rabi coupling, instead of the driving power. Our observation advances the understanding of ultrastrongly-coupled systems and paves the way to study high-order processes in the quantum Rabi model.

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Characteristic spectra of circuit quantum electrodynamics systems from the ultrastrong to the deep strong coupling regime

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We have measured spectra of circuit QED systems, where the coupling strength g is much larger than the transition frequency of the qubit Δ and is around 70% of the resonance frequency of the oscillator ω. These coupling strengths lie between the ultrastrong [1] and deep strong coupling [2] regimes. We have also performed a systematic analysis of the expected spectra for different values of the coupling strength ranging from the ultrastrong to the deep strong coupling regimes. We show that as the coupling strength increases, the spectrum of a circuit-QED system undergoes multiple qualitative transformations, such that five ranges are identified, each with its own unique spectral features. The spectra in this study, in combination with those of Refs. [1,2], cover four of these five intervals. In all cases the spectral features are consistent with the parameter values extracted from a systematic fitting of the full spectra. These results lead to a quick and simple method for obtaining a rough estimate of the parameter g/ω simply by looking at the overall features in the spectrum [3].

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Coherent-incoherent phase transition of virtual photons in superconducting circuit

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In the ultra-strong light-matter interaction regime, there are so-called virtual photons in the ground state. While the expectation number of photons is surely not zero, the expectation value of photonic amplitude (annihilation operator) is usually zero [1]. However, it was proposed around 1970 [2] that the virtual photons can get a coherent amplitude spontaneously in the ground state and also in the thermal equilibrium when the strength of the light-matter interaction is beyond a critical value in the ultra-strong regime. This is called the super-radiant phase transition (SRPT). Although a non-equilibrium analogue has been demonstrated experimentally [3], the thermal-equilibrium SRPT is not yet realized. The so-called no-go theorem of it in atomic systems was proposed around 1980 [4], and its possibility in superconducting circuits was under debate in recent years [5], where capacitive coupling between artificial atoms and bosonic modes was considered. In contrast, we propose a different circuit structure where a LC resonator and Josephson junctions are coupled via inductances in parallel [6]. The Hamiltonian is derived in the standard quantization procedure, and it is described as a bosonic mode (photon) interacting with anharmonic oscillators (atoms). The existence of a SRPT is examined in the semi-classical approach in the limit of an infinite number of junctions [4]. We also perform numerical diagonalization of the Hamiltonian with a finite number of junctions and observe an asymptotic behavior approaching the infinite limit as the number of junctions increases.

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Cavity quantum electrothermodynamics with rotational degrees of freedom

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When the energy exchange between an optically active dipolar transition and a resonant electromagnetic cavity mode becomes faster than any relaxation process, we enter the so-called strong coupling regime. In systems where many independent dipoles are coupled with the same cavity photonic mode, the light-matter coupling scales superradiantly with the square root of the number of dipoles [1], making it possible to modify the coupling by engineering the dipole density. The normal modes of those systems are called polaritons, quasi-bosonic [2] half-light and half-matter quasi-particles. In general the coupling of a dipole with the photonic field will depend on its microscopic degrees of freedom, like its orientation or vibrational state. As the energy of the coupled light-matter system depends upon the interaction strength, this will translate into an optomechanical force exerted by the cavity on the dipole. When many dipoles are superradiantly coupled to the same cavity mode, it is shown that this would in turn lead to the emergence of cavity quantum electrothermodynamic effects, where the intensity of the coupling with the photonic field has a thermodynamic impact upon the microscopic configuration of the dipoles.
In most cases the light-matter coupling strength of a single dipole x is much smaller than the temperature of the system, but the superradiantly enhanced coupling $\Omega \simeq pNx$, with N the number of coherently coupled dipoles, can easily exceed it. Whether the strength of the optomechanical force exerted on each dipole scales with x or Ω will thus determine if those effects are experimentally observable. This problem has generated a remarkable interest [3, 4, 5, 6, 7] and it has been recently addressed in two distinct theoretical works [6, 7], investigating impact of strong lightmatter coupling in molecular systems on underlying degrees of freedom. Both works arrive at the same conclusion, namely that while observables depending on the energy of the polaritonic states feel the superradiant coupling Ω, the relevant energy scale for effects influencing internal degrees of freedom of individual molecules is the single molecule coupling x. Those effects are thus washed out by thermal fluctuations. We demonstrate that this situation can be overcome in excited systems, in which an high macroscopic density of excitations is present. Not

only this allows to reach a regime in which cavity quantum electrothermodynamic effects are observable, but also to explore the full dynamical range of the system using the excitation density s as an effective temperature knob. Our aim is to give a proof of concept for the means to harness optomechanical effects due to superradiant strong light-matter coupling for manipulating the thermodynamic properties of microscopic degrees of freedom associated with each dipole. In order to give an example of this thermodynamic effects we investigate a superradiant cavity quantum electrodynamic setup in which the dipoles coupled to the cavity photonic mode can freely rotate, modifying their alignment and thus their coupling with the cavity field. By exploiting the formal equivalence of a set of rotating dipoles with a polymer we are able to calculate the partition function of the coupled system and to demonstrate it exhibits a second order phase transition between a bunched state of isotropic orientations and a stretched one with all the dipoles aligned, as it moves from a low to an high polaritonic excitation density state. Our intuitions are supported by both numerical and analytical results. The investigated effect can be observed as an intensity-dependent shift of the polaritonic resonances in free-floating, strongly coupled organic molecules.

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A Quantum Tale in the USC regime: 1 Photon, 2 Atoms and 3 Cavities

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Ultrastrong light-matter interaction enables novel and fascinating physical effects, that are very promising for future quantum technologies. A recent paper by Garziano et al. (Phys. Rev. Lett. 117, 043601 (2016)) shows that two separate two-level atoms, interacting with a single-mode optical or microwave resonator, can simultaneously be excited by a single photon. Here we present results that extend and generalize the novel physics above mentioned. Specifically, we consider the absorption of a single photon by two spatially separated two level atoms, embedded into an array of three coupled optical cavities. The atoms are ultrastrongly coupled to their own cavity mode, and the cavities are weakly coupled in a open chain configuration, where the central element connects those interacting with atoms: (=)( )(=). We show that also in this case the process can occur. We investigate the dynamics under different excitation conditions, and provide answers to causality issues raised by this phenomenon.

Novel frontiers in quantum vacuum emission

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I will investigate the effect of losses and detuning on quantum vacuum emission. Using a non-perturbative approach I will prove that their impact is limited, to the point that the system can transition from the strong to the weak coupling regime without any appreciable impact on the intensity of the quantum vacuum emission.

Quantum heat current under nonperturbative and nonMarkovian conditions: Application to heat machines

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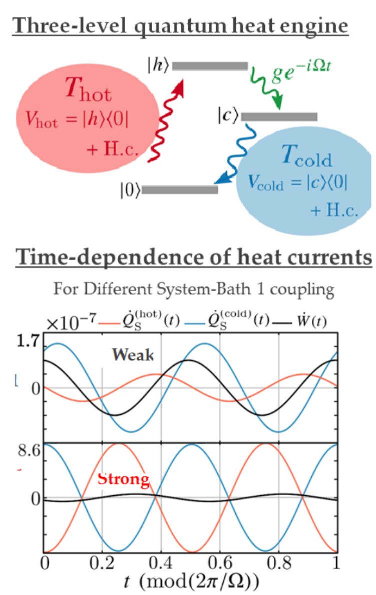
Quantum heat transport problems involving quantum heat machines have been studied with approaches developed through application of open quantum dynamics theory. Moreover, the advent of micro-technology allows us to investigate quantum heat current experimentally. In quantum case, system-bath entanglement as well as bath-bath entanglements play essential role to characterize the thermodynamic behavior of a system that interacts with thermal environments. In this talk, we first derive reduced hierarchy equations of motion (HEOM) [1,2] from correlated thermal equilibrium state,[3,4] which can deal with non-Markovian and non-perturbative system-bath interactions at finite temperature without approximation. Building on these results, we show that the violation of the positivity condition encountered in many other reduced equation of motion approaches results from the Markovian assumption [2, 3].

We then numerically demonstrate roles of systembath entanglement as well as bath-bath entanglements for a spins-Bosons system [5] and three-level heat engine model [6] under non-equilibrium condition using HEOM approach. We observe cyclic behavior of the heat currents and the work performed by the heat engine, and we find that their phases depend on the system-bath coupling strength. Through consideration of the bath heat current, we show that the efficiency of the heat engine decreases as the strength of the system-bath coupling increases, due to the contribution of correlations among system-bath interactions (CASBI).



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Engineering mechanical quantum states in USC optomechanics

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I present recent results showing how the USC regime of cavity-optomechanics ca be used to efficiently synthesize mechanical quantum states. In the first part of the talk, I will describe a strategy for the preparation of arbitrary quantum superpositions of mechanical Fock states. The proposed scheme consists of a single step where all the classical optical excitations are sent for a common time interval [1]. In the second part I present an algorithm for the preparation of maximally entangled mechanical NOON states in a completely controlled and deterministic manner with quite high Fock states within a few-step protocol [2]. The efficiency and robustness of these protocols is tested by calculating fidelities and Wigner functions in presence of decoherence, thermal noise, and imperfect cooling.

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Observation of collective coupling between an engineered ensemble of macroscopic artificial atoms and a superconducting resonator

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A hybrid system composed of many qubits and a common field such as cavity quantum electrodynamics may provide a way to realize the ultra-strong coupling regime. One well known example is superconducting circuits coupled to ensembles of microscopic natural atoms. In such cases, the properties of the individual atom are intrinsic, and so are unchangeable. However, current technology allows us to fabricate large ensembles of macroscopic artificial atoms such as superconducting flux qubits, where we can really tailor the properties such as a coupling strength and resonant frequency. Here, we demonstrate coherent coupling between a microwave resonator and several thousand superconducting flux qubits, where we observe a large dispersive frequency shift in the spectrum of 250 MHz induced by collective behavior [1]. These results represent the largest number of coupled superconducting qubits realized so far, opening up a new way to realize the ultra-strong coupling.

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Quantum Memory in Deepstrong Coupling Regime

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Quantum memories are important elements for quantum information processing applications. Here we show that a two-level system deepstrong coupled with a cavity mode, when the parity symmetry of the Rabi Hamiltonian is broken, can be used to store and retrieve quantum information. We make use of an auxiliary atomic decoupled level [1] and of the lowest two eigenstates of the symmetry broken Rabi Hamiltonian, where we find there is a strong suppression of decoherence in the relaxation channel T_1. To preserve decoherence from pure dephasing channel T_φ, we prove it is possible to apply the dynamical decoupling procedure. This proposal is experimentally realizable in superconducting circuits, as the deepstrong coupling has been recently achieved [2] and the dynamical decoupling has been realized [3].

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Ground-state physics in ultra-strong coupled light-matter systems

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When light and matter are ultra-strongly coupled, the eigenstates of the system can be written as a coherent superposition of states describing bare excitations. As an exemplifying consequence, the average photon number is non-zero even the ground state. This “virtual” photon population can be probed in different ways as non-adiabatic modulations of the light-matter coupling inducing transitions outside the interacting Hilbert space [1,2].
Similarly, in [3], we show that the dressed structure of the ground state can lead to a new channel for electroluminescence, i.e. the emission of light when current flows through a system. While standard electroluminescence relies on the population of excited states followed by spontaneous emission, the process we describe extracts bound photons by the dressed ground state and it has peculiar features to distinguish it from usual electroluminescence.
While the dressed structure of the ground state can be probed by disturbing its internal coherences (as in the example presented above), it is also possible to introduce less disruptive methods. In [4], we propose to use a time-dependent opto-mechanical interaction, allowing a mechanical probe to provide an amplified measurement of the virtual photons dressing the quantum ground state of an ultra strongly-coupled light-matter system.

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