

Observation of quantum phase transitions with emergent entanglement in circuit QED systems

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This report focuses on quantum phase transitions (QPTs) accompanied by emergent entanglement in circuit QED systems. Two sets of experiments are presented to demonstrate the emergence of nonclassical entangled states along with the QPTs. In the first set of experiments [1,3], a controllable quantum Rabi model (see Fig. 1) is constructed. As the system is tuned across the critical point, the cavity field undergoes a transition from a normal phase to a superradiant phase characterized by Schrödinger cat state superpositions with pronounced quantum interference. Wigner tomography is employed to comprehensively characterize the light-matter hybrid state, revealing strong nonclassical features of the field and its entanglement with the qubit. In the second experiment [2], a multiqubit Lipkin-Meshkov-Glick (LMG) model is realized (see Fig. 2), where spontaneous symmetry breaking (SSB), purely due to quantum effects, is observed alongside the generation of multiqubit GHZ-state entanglement. The Hamiltonian of the system captures the competition between continuous driving and intra-qubit interactions. In this experiment, six Xmon qubits are nearly homogeneously coupled via a common bus resonator. By slowly decreasing the drive strength, a quasi-adiabatic evolution is achieved, in which the initial symmetric product state evolves into a superposition of two degenerate symmetry-broken eigenstates. The gradual enhancement of Z_2 symmetry breaking is observed in real time by measuring average two-qubit longitudinal correlations. The quantum nature of the SSB process is further confirmed via measurements of multiqubit transverse correlations and Wigner function. The results highlight the fundamental difference between the SSB in QPT of many-body systems and that in classical phase transitions, offering new insights into QPTs in finite-size quantum systems: (1) In finite-size systems, SSB corresponds to GHZ state generation (SSB = GHZ); (2) In the thermodynamic limit ($N \rightarrow \infty$), decoherence scales linearly with N , leading to the loss of quantum coherence; (3) GHZ-type entanglement provides a criterion for distinguishing QPTs in finite quantum systems from those in the thermodynamic limit.

Cavity Controls Core-to-Core Resonant Inelastic X-ray Scattering

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X-ray cavity quantum optics with inner-shell transitions has been hindered by the overlap between resonant and continuum states. Here, we report the first experimental demonstration of cavity-controlled core-to-core resonant inelastic x-ray scattering (RIXS). We eliminate the effects of the absorption edge by monitoring the RIXS profile, thereby resolving the resonant state from the overlapping continuum. We observe distinct cavity-induced energy shifts and cavity-enhanced decay rates in the 2p3d RIXS spectra of WSi₂. These effects, manifesting as stretched or shifted profiles in the RIXS planes, enable novel spectroscopic applications by cavity-controlled core-hole states. Our results establish core-to-core RIXS as a powerful tool for manipulating inner-shell dynamics in x-ray cavities, offering new avenues for integrating quantum optical effects with x-ray spectroscopy.

Intensity correlation imaging: From quantum ghost imaging to classical single-pixel imaging

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In the 1950s, R. Hanbury Brown was the first to measure the spatiotemporal correlations of photons to determine the angular diameter of stars, which laid the foundation for the development of photon statistics and subsequently the whole new field of quantum optics. In 1995, quantum “ghost” imaging was first demonstrated with entangled photon pairs from parametric downconversion. Later, this extended into the broader field of classical intensity correlation imaging, encompassing classical ghost imaging, single-pixel imaging, structured illumination imaging and other types of unconventional imaging based on second-order correlations—these may now be grouped under the umbrella of “quantum inspired” imaging. Research has now covered the entire electromagnetic spectrum, and has even extended to atoms, electrons and neutrons. A key feature of ghost imaging is that it does not require an array detector like a CMOS or CCD camera but uses only a single-pixel detector to obtain a two-dimensional image; as a result, imaging can be realized faster and under very low illumination conditions, through a scattering turbulent medium, and even with higher resolution. Formerly, exposing and reconstructing an image required several hours or even days, but technology has now advanced such that real time imaging of moving objects is now realizable. This presentation will introduce the latest progress in ghost imaging by our group in the Institute of Physics, Chinese Academy of Sciences. Real-time spectral single-pixel imaging has been achieved in the visible [1] and near-infrared bands; imaging at single-photon levels [2], and spectral ghost imaging of different components of objects in the X-ray region [3], as well as fast X-ray ghost imaging [4] have also been demonstrated. Finally, future application prospects will be briefly discussed.

1. Yue-Xi Zhang et al., Opt. Exp. 32, 47216 (2024).
2. Zi-Qing Zhao et al., Opt. Lett. 50, 169 (2025).
3. Jin-Tao Xie et al., Opt. Lett. 49, 4162, (2024).
4. Jin-Tao Xie et al., Photonics Res. (2025), in press.

Closed and open unbalanced Dicke trimer model: Critical properties and nonlinear semiclassical dynamics

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We study a generalization of a recently introduced Dicke trimer model [Phys. Rev. Lett. 128, 163601 (2022); Phys. Rev. Res. 5, L042016 (2023)], which allows for cavity losses and unbalanced light-matter interactions (in which rotating and counter-rotating terms can be tuned independently). In the original description of a Dicke trimer, three Dicke models are coupled in a ring topology via a complex photon hopping whose complex phase describes a synthetic magnetic field threading the loop. This original model features several intriguing equilibrium phases and critical phenomena such as frustrated superradiance, two-critical scalings in the frustrated superradiant phase, and finite critical fluctuations in the anomalous normal phase. Here, we find that in the extreme unbalanced limit, where only rotating terms are present, the $U(1)$ symmetry of the Tavis-Cummings model is restored, qualitatively altering the critical phenomena in the superradiant phase due to the presence of a zero-energy mode. To analyze this general regime, we develop a semiclassical theory based on a requantization technique. This theory also provides further physical insight on recently reported anomalous finite critical fluctuations in the time-reversal broken regime. Moving to the open-Dicke case, by introducing local dissipation to the cavities, we observe the emergence of a rich range of nonequilibrium phases characterized by trivial and nontrivial dynamical signatures. In the former case, we identify, when time-reversal symmetry is present, a new stationary phase that features superradiant states in two of the three cavities and a normal state in the other cavity. In the latter case, we observe the emergence of dynamical phases in which the system exhibits superradiant oscillations, characterized by periodic or chaotic phase space patterns. The landscape of transitions associated with these dynamical phases features a wide range of qualitatively different behaviors such as Hopf bifurcations (followed by period-doubling cascades or quasiperiodic oscillations), anomalous Hopf bifurcations (with burst-oscillation-like post-bifurcation dynamics), collisions between basins of attraction (associated with different symmetry-broken equilibria), and exterior crises (featuring transient chaotic dynamics). We highlight how the two-critical-scalings feature of the closed model is robust under dissipation (with doubled critical exponents) while the phenomenon of anomalous finite critical fluctuations becomes a mean-field scaling (as a consequence of Hopf bifurcations of the equilibria featuring the normal state) in the open model.

On-axis energy backflow in tightly focused hybrid vector beams

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Optical energy backflow is an intriguing counterintuitive phenomenon, which has been reported in the focal region of light beams with phase or polarization singularities. Nevertheless, the possibility of achieving on-axis energy backflow near the focus of tightly focused hybrid vector beams remains unclear. Here, we demonstrate analytically and numerically that the on-axis energy backflow effect can be achieved in the tightly focused fields of hybrid vector beams, including the conventional cases presenting circular polarization mapping tracks on the Poincaré sphere for azimuthal polarization states and the unconventional cases characterized by noncircular polarization mapping tracks featuring noncircular mapping tracks on the Poincaré sphere. Theoretically, based on the Richards-Wolf vectorial diffraction integral, we give the general expressions for all components of the electric and magnetic fields near the focus, as well as the expression for the longitudinal component of the Poynting vector in the focal plane. Significantly, we reveal that the on-axis energy backflow will appear when the amplitude modulation factor l and the topological charge m of the vortex phase carried by basis vectors satisfy the condition $|l| - |m| = \pm 2$. Moreover, we find that the longitudinal component of the Poynting vector is not circularly symmetric but related to the azimuthal angle in the focal plane for the hybrid vector beams with nonzero l and m . Furthermore, it is found that the on-axis energy backflow can also be observed in the focus of the hybrid vector beams under other basis vectors beyond the x - y case. And we surprisingly uncover that the on-axis energy backflow can also be observed in the focus of the linearly polarized optical vortex with the topological charge being ± 2 , where the near-axis energy flows spirally along the optical axis. The numerical simulation results are in good agreement with the theoretical analyses.

Interplay between Nonreciprocity and Geometric Frustration: Chiral Frustrated Self-Organization of BECs in an Optical Cavity.

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Nonreciprocal interactions often create conflicting dynamical objectives that cannot be simultaneously satisfied, leading to nonreciprocal frustration. On the other hand, geometric frustration arises when conflicting static objectives in energy minimization cannot be satisfied. In this work, we show that nonreciprocal interaction among three collective quantum spins, mediated by a damped cavity, induces not only nonreciprocal frustration, intrinsic to nonreciprocity, but also geometric frustration with a remarkable robustness against disorder. This ensures that the accidental degeneracy of steady states remains intact even when the system is perturbed away from a fine-tuned point of enhanced symmetry, in sharp contrast to the equilibrium case. Leveraging this finding, we identify a nonreciprocal phase transition driven by both geometric and nonreciprocal frustration. It gives rise to a time-dependent state, which shows chiral dynamics along a geometry shaped by the geometric frustration, thereby dynamically restores the broken discrete symmetries. Moreover, it constitutes a time-crystalline order, with multiple harmonics set by an emergent time scale that exhibits critical slowing down. Our predictions have important physical implications for a three-component spinor BEC-cavity system, which manifest as a geometric frustration in the structural phase transition and chiral dynamics of the frustrated self-organized BECs. We demonstrate the feasibility of experimental observation despite the presence of disorder in the spin-cavity coupling strengths.

Enhancement of spectral broadening from femtosecond laser pulses in low-pressure air-plasma

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High-energy femtosecond supercontinuum source with high beam quality is crucial for high-peak-power few-cycle pulse generation. However, simply increasing the peak power of femtosecond pulses to enhance spectral broadening often leads to multiple filamentation, which degrades the spatial beam quality and spectrum coherence. In this study, we present a novel approach that introduces uniform plasma into low-pressure air to achieve sufficient spectral broadening with high energy density while preserving a single filamentation mode. Our simulations reveal that the enhancement of the spectral broadening in the low-pressure air is attributed to the extended filamentation length, supported by energy confinement in the temporal domain due to the negative dispersion of the pre-plasma. This approach provides a promising pathway for generating few-cycle pulses with high energy.