Quantum nonlinear optics with Rydberg polaritons

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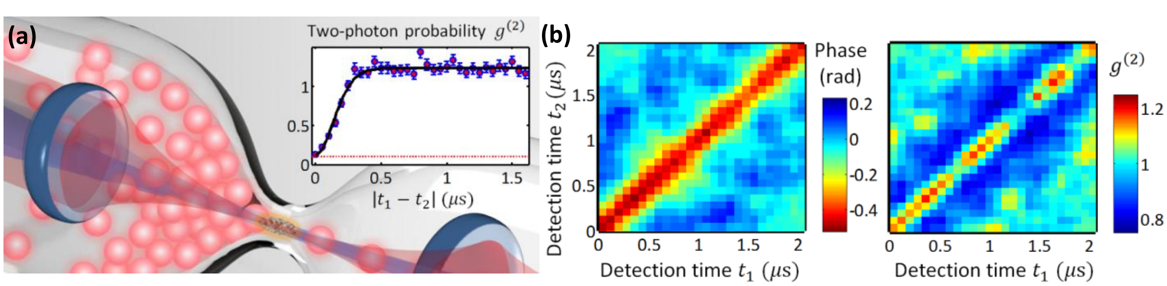
Achieving strong interactions between photons has been at the forefront of quantum-optics research for decades. As a fundamental tool for 'quantum by quantum' control of light fields, these interactions could be used to realize gates for quantum computing and produce correlated optical states for precision measurements. Furthermore, they could enable the exploration of new quantum states and phases, similar to those explored in strongly correlated particle systems. This long-term goal was recently realized with both dissipative [Nature **488**, 57 (2012)] and dispersive [Nature **502**, 71 (2013)] interactions between individual photons.

The interaction is mediated in a gas of cold atoms by coupling the photons to Rydberg states with principle quantum number n=100. Owing to their huge dipole moment, the Van der Walls potential between Rydberg atoms is substantial at distances as large as 10 μm. A photon in the medium is converted into a *Rydberg polariton*, a mutual excitation of light and matter with an effective mass. The polaritons slow down to 100 m/s, indicating they are predominately Rydberg excitations. Thus individual photons effectively acquire large electric dipoles, long-range interactions, and mass.

In the dissipative regime, a photon in our medium blocked proximal photons with 95% probability. In the dispersive regime, we measured a phase shift of 1 radian for two photons, close to the value π required for quantum gates and ×100 stronger than previously demonstrated Kerr media. We established that the quantum dynamics is governed by a two-photon bound-state, supported by the effective attraction between photons. This dynamics produced entangled photon pairs from initially independent photons.



(a) **Dissipative** interaction prevents the transmission of more than one photon at a time. The outgoing photons rate is independent of the incoming rate and saturates at 1/μs, realizing a photonic 'hourglass'. The two-photon correlation $g^{(2)}$ displays the anti-bunching. (b) **Dispersive** interaction alters the optical phase for two simultaneous photons (left). The lower effective energy of proximal photons leads to an attractive force and bunching (right).