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Strongly interacting photons in a quantum nonlinear medium

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Photons are fast and robust carriers of information but their lack of mutual interactions hinders their use in quantum information protocols. Interactions can be mediated by nonlinear media, and optical nonlinearities at the single photon level are a long-standing goal of quantum optical science. By coherently coupling slowly propagating photons to Rydberg states in a dense cold atomic gas, we create a single-pass medium with large photon-photon interactions. We first demonstrate that combining electromagnetically induced transparency techniques with the Rydberg blockade effect leads to strong dissipative interactions between individual photons. As a result, the simultaneous propagation of photons is suppressed in an otherwise transparent medium, and coherent laser pulses are converted into single photons. We subsequently explore the regime of coherent interactions, where simultaneously propagating photons acquire a large conditional phase-shift and become entangled. In this regime, the photons behave as massive particles exerting an attractive force onto each other and their evolution is governed by the existence of a photonic bound-state. This work paves the way for cavity-free deterministic optical quantum gates and quantum many-body physics with light.