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Dipolar polariton collisions: Rydberg nonlinear optics with multi-level transitions

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We study the effective interaction between photons that travel as slow polaritons in an atomic gas. When the polaritons are counter-propagating and comprise Rydberg states of opposite parity, the collision between them is dominated by a resonant dipolar exchange. Owing to the long range of the dipole-dipole interaction, blockade processes are forestalled and their deficiencies avoided. We show that the robust conditional phase shift associated with this collision can be employed for generating maximally-entangled cluster states of photons. To form odd-parity polaritons, we utilize a three-photon ladder transition to the Rydberg level. Under certain conditions, this ladder scheme supports conventional slow-light polaritons while offering additional advantages, such as access to stronger orbital transitions, full or partial Doppler-free arrangements, and flexibility in tailoring a desired nonlinear optical response. In particular, we demonstrate tailoring of this scheme for counteracting motional dephasing and for recovering the homogenous absorption cross-section of inhomogeneously-broadened media.