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Phase-controlled quantum optomechanics

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Quantum entanglement, featuring nonclassical correlations between distinct and usually spatially separated systems, is one of the key traits of quantum physics. By creating and sharing entangled states between different nodes in a quantum network, a variety of novel quantum technologies well beyond the abilities of classical devices can be realized, ranging from quantum sensing to quantum information processing or communication. However, due to inevitable imperfections of solid-state devices such as Rayleigh backscattering caused by surface roughness or material inhomogeneity, a severe challenge always exists in practice, i.e., how to protect quantum coherence or the quality of entanglement against random losses or environmental noises. In this issue of SCPMA, Liu et al. [1] proposed an elegant and feasible scheme to achieve robust quantum entanglement of photons and phonons in a highly asymmetric way, by tuning the phases of driven lasers in an optomechanical resonator. This work is inspired by a very recent experiment demonstrating synthetic gauge fields in phase-controlled optomechanics and their applications in achieving nonreciprocal transmissions of light [2]. Based on this experiment [2], Liu et al. [1] found that the essentially same phase-controlled technique also provides a new strategy to engineer purely quantum properties of optomechanical systems.

In previous studies, synthetic gauge fields have been mostly realized by using complex real-space structures, which can be difficult to be used for quantum state engineering. In contrast, very recently, experimentalists found a way to achieve well-tunable synthetic gauge fields in a single microresonator, by using virtual lattices formed by the optical and mechanical modes [2-5]. More importantly, the effective magnetic flux can be precisely controlled by adjusting the phase differences of the external driving lasers, thus providing a way to realize nonreciprocal optical transmissions and one-way frequency conversion of photons [2, 3, 6]. Similar mechanisms have been applied to microwave photons in superconducting circuits [7-9]. These pioneering works offer new opportunities to engineer various quantum optomechanical effects by utilizing the power of synthetic gauge fields. The work of Liu and his coworkers [1] is the first step along this line, predicting a feasible way to achieve asymmetric control of steady-state optomechanical entanglement by using the synthetic gauge field. In particular, they show that by tuning the phase difference of the counterpropagating driving fields in the resonator, the asymmetric optomechanical entanglement provides a conceptually new way to enhance the quality of entanglement in a specific direction, even in the presence of backscattering losses. This is reminiscent of the recent proposal on realizing nonreciprocal quantum entanglement by breaking the time-reversal symmetry in a spinning device, which is also confirmed to be robust against optical backscattering losses in a specific direction [10]. The advantage of the work of Liu et al. is that it does not need any mechanical rotation of the device and is more feasible in practice, thus opening up new ways to protect and engineer various quan-

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*Corresponding author (email: chunhua@ustc.edu.cn) tum effects in a wide range of neutral systems with synthetic gauge fields.

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