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Stroboscopic High-Order Nonlinearity in Optomechanics

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Abstract

High-order quantum nonlinearity is an important prerequisite for the advanced quantum technology leading to universal quantum processing with large information capacity of continuous variables. We devise a method of stroboscopic application of a highly nonlinear potential to an initial squeezed thermal state of a mechanical oscillator of an optomechanical cavity. The mechanical states generated by the protocol exhibit nonclassicality proving the higher-order quantum nonlinearity and rendering them a useful resource for the mechanical quantum technology. We analyze the main sources of decoherence and estimate possible achievable nonlinearities in the systems that are within reach with the current levitated optomechanical experiments.

Quantum Information Processing with continuous variables (CVs) has achieved noticeable progress recently [1]. In order to fully gain the benefits of CVs and to potentially access the universal quantum computation one at least requires a nonlinear cubic potential [2]. A straightforward way to achieve the nonlinearity is to induce controllable nonlinear force on a linear oscillator. A promising candidate to do so can be found in the field of optomechanics [3] that focuses on the systems in which radiation pressure of light or microwaves drives the mechanical motion. The optomechanical systems have reached a truly quantum domain demonstrating the effects ranging from the ground state cooling [4] to the entanglement of distant mechanical oscillators [5]. Of particular interest are the levitated systems in which the trapping potential of the mechanical motion is provided by an optical tweezer [6]. Besides the inherently nonlinear optomechanical interaction met in the standard bulk optomechanical systems the levitated ones posses the attractive possibility of engineering the nonlinear trapping potential [7].

In the present letter we propose a high-order nonlinearity for optomechanical systems with time variable external force. We theoretically investigate the dynamics of a levitated nanoparticle in presence of simultaneously a harmonic and a strong stroboscopically applied nonlinear potentials enabled by the engineering of the trapping beam. Using Suzuki-Trotter expansion we induce the simultaneous action of the potentials and obtain the Wigner functions of the quantum motional states achievable in this system. We directly observe nonclassical negative Wigner function generated by highly nonlinear quantum interaction. The oscillations of Wigner function reaching negative values witness the quantum dynamics required for nonlinear phase gate. We prove a nonlinear combination of the canonical quadratures of an oscillator to be squeezed below the ground state variance that is an important prerequisite of this state being a resource for the measurement-based quantum computation. We focus our attention to realistic versions of nonlinear phase states, namely the cubic phase state. The method allows straightforward extension to more complex nonlinear potentials which can be used to flexibly generate other resources for nonlinear gates and their applications.

[1] S. Braunstein and P. van Loock, Reviews of Modern Physics **77**, 513 (2005); A. Orieux and E. Diamanti, Journal of Optics **18**, 083002 (2016).

[2] S. Lloyd and S. L. Braunstein, Physical Review Letters **82**, 1784 (1999); D. Gottesman, A. Kitaev and J. Preskill, Physical Review A **64**, 013210 (2001).

[3] M. Aspelmeyer, T. J. Kippenberg and F. Marquardt, Reviews of Modern Physics **86** (2014).

[4] J. D. Teufel *et al.*, Nature **475**, 359 (2011), J. Chan *et al.*, *ibid* **478**, 89 (2011).

[5] R. Riedinger *et al.*, Nature **556**, 473 (2018), C. F. Ockeloen-Korppi *et al.*, *ibid* **556**, 478 (2018).

[6] P. F. Barker and M. N. Shneider, Physical Review A **81**, 023826 (2010); D. E. Chang *et al.*, PNAS **107**, 1005 (2010); O. Romero-Isart *et al.*, Physical Review A **83**, 013803 (2011);

[7] A. Bérut *et al.*, Nature **483**, 187 (2012); F. Ricci *et al.*, Nature Communications **8**, 15141 (2017); Šiler *et al.*, Physical Review Letters **131**, 230601 (2018).