# Scalable quantum simulation of pulsed entanglement and Einstein-Podolsky-Rosen steering in optomechanics

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Optomechanical oscillators provide fundamental tests of mesoscopic quantum mechanics, and have potential technological applications to ultra-sensitive measurement. Impressive success in cooling optomechanical systems has resulted in a recent observation of entanglement of a microwave field with a mechanical oscillator, in an electromechanical experiment at JILA [1, 2]. This experiment is illustrated schematically in Fig (1), below .

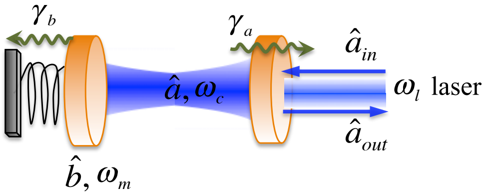

Figure 1. Two light pulses enter the cavity and interact with the mirror via radiation pressure. A first blue-detuned pulse entangles, while a second red-detuned pulse gives a read-out.

The next outstanding goal is to observe the *nonlocal quantum correlations* known as EPR-steering, as predicted by Einstein, Podolsky and Rosen in their famous EPR paradox, for mesoscopic massive objects. Such a realization would be a precursor to experiments that directly probe the macroscopic reality of an object. It is of fundamental interest, whether the two systems can show these strange directional “spooky action-at-a-distance” effects that Schrödinger called “steering” .

Here we carry out a fully exact, scalable, probabilistic quantum simulation of the standard nonlinear optomechanical model, in regimes allowing both entanglement and EPR-steering of the mechanical oscillator [3]. We study the dynamical generation of correlations between the oscillator and an output pulse for realistic parameters. In our simulations we utilize the exact positive-P (+P) phase-space method, which has a positive probability distribution for all quantum states. The simulations are in agreement with the JILA quantum entanglement experiment. We predict suitable parameter values for an EPR demonstration.

The standard, single-mode optomechanical model is used. The Hamiltonian includes the energy of the mechanical oscillator mode at $\omega_m$, an input at $\omega_l$, and the optical mode energy at angular frequency $\omega_o = \omega_l + \delta$. We transform to an interaction picture leaving:

$$\begin{aligned}\hat{H}/\hbar = \delta \hat{a}^\dagger \hat{a} + \omega_m \hat{b}^\dagger \hat{b} + \chi \hat{a}^\dagger \hat{a}(\hat{b} + \hat{b}^\dagger) \\ + iE(t)(\hat{a}^\dagger - \hat{a}) + \hat{H}_r .\end{aligned}$$

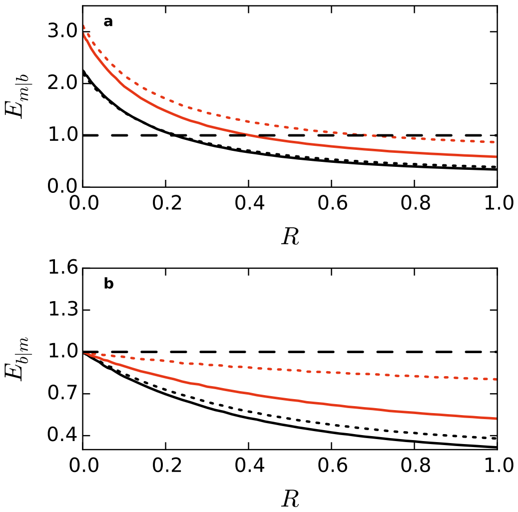

Figure 2. EPR-steering versus entanglement gain parameter $R$, for the optomechanical experiments. Dashed lines indicate the result of using optical readouts, solid lines assume direct oscillator measurements. Black and red curves are for $T_{bath} = 200mK$ and $T_{bath} = 4K$ respectively. EPR-steering of the mechanical system $m$ is possible if $E_{m|b} < 1$, and of the optical system if $E_{b|m} < 1$.

The optomechanical interaction is $\chi$, due to radiation pressure. A mapping to a probabilistic positive-P distribution exists for any quantum density matrix. The corresponding stochastic dynamical equations, including damping, are:

$$\begin{aligned} d\alpha &= \left\{E(t) - \left[i\delta_k + i\chi(\beta + \beta^+) + \gamma_o\right]\alpha\right\} dt + dW_1 \\ d\beta &= \left[-\left(i\omega_m + \gamma_m\right)\beta - i\chi\alpha\alpha^+\right] dt + dW_2 ,\end{aligned}$$

together with conjugate terms. Results for EPR simulations are shown in Fig (2), using typical parameter values from recent opto-mechanical experiments. Our main predictions are that Reid inequality violations signifying the EPR paradox are best obtained in the optomechanical rather than electromechanical regime, owing to the relatively high efficiency of optical detectors.

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