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Engineering continuous-variable entanglement in mechanical oscillators with optimal control

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We demonstrate an optimal quantum control strategy for the deterministic preparation of entangled harmonic oscillator states in trapped ions. The protocol employs dynamical phase modulation of laser-driven Jaynes-Cummings and anti-Jaynes-Cummings interactions. We prepare Two-Mode Squeezed Vacuum (TMSV) states in the mechanical motions of a trapped ion and characterize the states with phase-space tomography. First, we verify continuous-variable entanglement by measuring an Einstein-Podolsky-Rosen entanglement parameter of 0.0132(7), which is below the threshold of 0.25 for Reid's EPR criterion. Second, we perform a continuous-variable Bell test and find a violation of the Clauser-Horne-Shimony-Holt inequality, measuring 2.26(3), which is above the entanglement threshold of 2. We also demonstrate the flexibility of our method by preparing a non-Gaussian entangled oscillator state–a superposition of TMSV states.

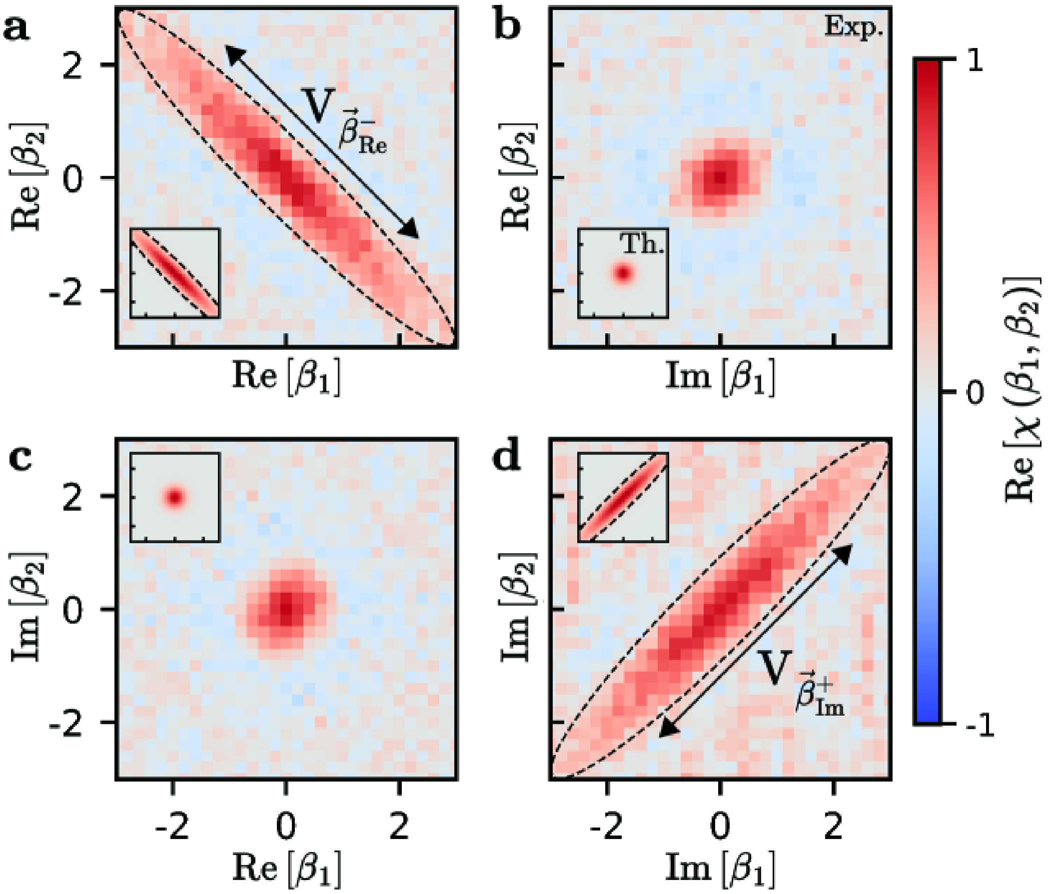

Figure 1:

Figure 1. Experimental characteristic function tomography of a two-mode squeezed vacuum (TMSV) state with target squeezing parameter,r=1. All panels show the real component of the two-mode characteristic function. Panels a. and d. exhibit anticorrelation and correlation, respectively, consistent with two-mode squeezing. Dashed lines plot the Gaussian functions that are fitted to the data, from which variances are extracted and used to quantify entanglement with Reid's EPR criterion. Panels b. and c. show negligible correlation, consistent with uncorrelated orthogonal quadratures. Insets show the theoretical target characteristic function obtained from numerical simulations.]1

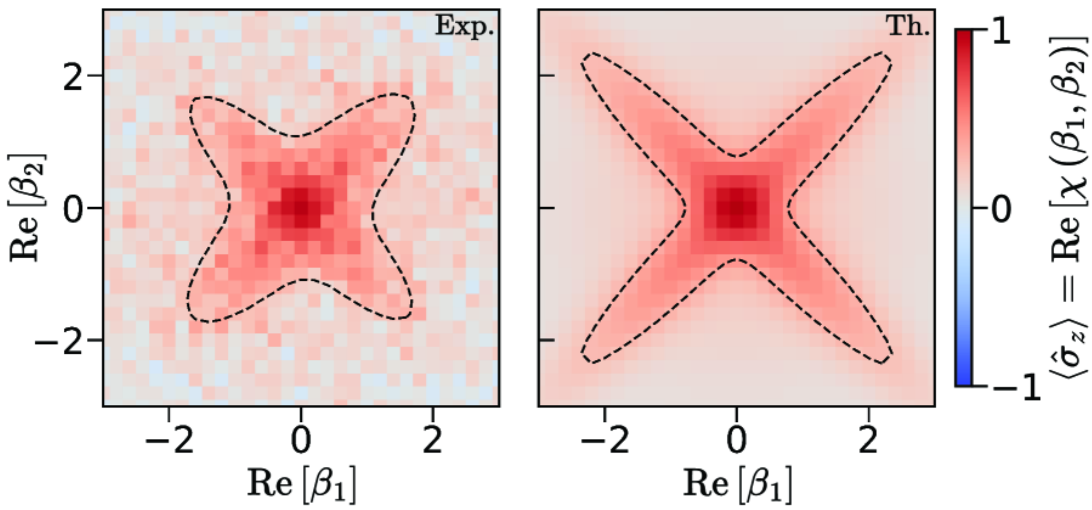

Figure 2:

Figure 2. Joint characteristic function reconstruction of an experimentally prepared superposition of TMSV states. The targeted state is an even superposition of two TMSV states. The experimentally reconstructed characteristic function shows features of the superposition state, with correlation along both axes, (β,$\pm\beta$). The characteristic function is fitted to a distinct sum of two two-dimensional Gaussian functions (dashed lines) to estimate the relative amplitudes and squeezing. Inset shows the theoretical target characteristic function obtained from numerical simulations.

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