

Stationary entanglement of a levitated oscillator with an optical field

Quentin Deplano^{1,2}, Antonio Pontin³, Francesco Marino^{3,2}, and Francesco Marin^{1,2,3,4}

1. Dipartimento di Fisica e Astronomia, Università di Firenze, via Sansone 1, I-50019 Sesto Fiorentino (FI), Italy

2. INFN, Sezione di Firenze, via Sansone 1, I-50019 Sesto Fiorentino (FI), Italy

3. CNR-INO, largo Enrico Fermi 6, I-50125 Firenze, Italy

4. European Laboratory for Non-Linear Spectroscopy (LENS), via Carrara 1, I-50019 Sesto Fiorentino (FI), Italy

Abstract: We demonstrate quantum entanglement between the center-of-mass motion of a levitated nanosphere and a propagating optical field, using cavity optomechanics at room temperature and phase-sensitive heterodyne detection.

Quantum entanglement between massive mechanical systems and optical fields is a key resource for quantum technologies and for probing the foundations of quantum mechanics. Optomechanical platforms have demonstrated remarkable control of mechanical motion, yet the realization of stationary entanglement between a mechanical oscillator and a propagating optical mode remains experimentally challenging. We demonstrate the generation and detection of quantum entanglement between the center-of-mass motion of a levitated nanosphere and an optical field, with correlations that persist in the propagating electromagnetic mode.

The experiment is based on a silica nanosphere (diameter ≈ 100 nm) optically trapped in a tweezer and accurately positioned on the axis of an optical cavity. The motion of the particle couples to the cavity field through coherent scattering of the trapping beams [1,2]. Two optical fields drive the cavity with opposite detunings: a red-detuned field cools and stabilizes the mechanical motion, while a blue-detuned field generates a two-mode squeezing interaction that entangles the mechanical oscillator with the optical mode [3].

Information about the quantum state of the system is extracted from the cavity output using phase-sensitive heterodyne detection. From the measured signals we reconstruct the full spectral correlation matrix of the outgoing fields and obtain the covariance matrix describing the joint optical–mechanical Gaussian state. Entanglement is quantified using the smallest symplectic eigenvalue of the partially transposed covariance matrix. We observe a violation of separability bounds, corresponding to a logarithmic negativity up to $E_N \approx 0.12$, demonstrating the presence of stationary optomechanical entanglement at room temperature.

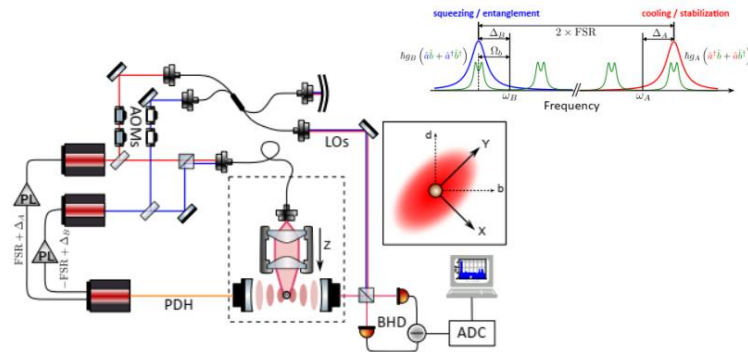


Fig. 1 Experimental configuration for generating optomechanical entanglement. A silica nanosphere is optically trapped in a tweezer and positioned inside an optical cavity. Two optical fields drive the cavity with opposite detuning: the red-detuned field cools the mechanical motion while the blue-detuned field produces a two-mode squeezing interaction that generates entanglement between the mechanical oscillator and the optical field. The cavity output is measured via heterodyne detection to reconstruct the optical–mechanical correlations. From Ref. [3].

References

- [1] A. Ranfagni, P. Vezio, M. Calamai, A. Chowdhury, F. Marino, and F. Marin: “Vectorial polaritons in the quantum motion of a levitated nanosphere”, *Nat. Phys.* **17**, 1120 (2021). A. Ranfagni, F. Marino, and F. Marin: “Spectral analysis of quantum field fluctuations in a strongly coupled optomechanical system”, *Phys. Rev. Lett.* **130**, 193601 (2023).
- [2] Q. Deplano, A. Pontin, A. Ranfagni, F. Marino, and F. Marin: “High purity two-dimensional levitated mechanical oscillator”, *Nat. Commun.* **16**, 4215 (2025)
- [3] Q. Deplano, A. Pontin, F. Marino, and F. Marin, “Stationary entanglement of a levitated oscillator with an optical field”, arXiv:2602.03456