Contribution ID: **84** Type: **Talk**

Remote entanglement of optically levitated nanoparticles

Tuesday, 7 May 2024 16:30 (30 minutes)

Optomechanics studies the interaction of light with moving objects, an essential resource for sensing, metrology, and the investigation of fundamental aspects of quantum mechanics with mesoscopic systems. By eliminating clamping losses and the background gas, optically levitated objects can reach an extreme degree of isolation from the environment, enabling free-space quantum control of mechanical motion even at room temperature [1]. Furthermore, the light mass and low dissipation of levitated oscillators results in remarkable force sensing capabilities [2]. Recent works showed that levitated particles in distinct optical tweezers can be coupled via Coulomb or optical binding forces at micron-scale distances [3]. Coupling strengths exceeding the total decoherence rate are a prerequisite to generate motional entanglement among nanoparticles. While Coulomb-mediated entanglement has been recently proposed as a mean to probe force-gradients below the standard quantum limit [4], entanglement via optical forces cannot be achieved in free space in absence of some reservoir engineering [5].

Our analysis shows how to entangle the motion of two optically levitated nanoparticles held by optical tweezers at a dozen meter distance solely harnessing optical forces. The scheme relies on the directional circulation of the light scattered off the nanoparticles via optical transmission lines. Interference with the background laser field both renormalizes the optical density of states and induces a two-mode squeezing interaction that can be adjusted via the transmission line phase. We analyse the system dynamics and show that both transient and conditional state entanglement between distant nanoparticles can be achieved for realistic experimental conditions.

[1] L. Magrini et al. - Nature 595, 373-377 (2021)
[2] C. Gonzalez-Ballestero et al. - Science 374, 6564 (2021)
[3] J. Rieser et al. Science 377 (6609), 987-990 (2022)
[4] H. Rudolph et al. PRL 129 (19), 193602 (2022)
[5] H. Rudolph et al. arXiv:2306.11893 (2023)

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Session Classification: Talks