

Entanglement of massive, charged objects via a lossy conductive wire**L. Papa^{*1}, C. Gonzalez-Ballester**¹Institute for Theoretical Physics, TU Wien, Wiedner Hauptstrasse 8-10/E136, 1040 Vienna, Austria

Bringing ever larger masses into quantum states not only benchmarks the amount of achievable quantum control and sensitivity of mechanical sensors, but also provides a pathway towards exploring untested physics like exotic particles or quantum gravity. While Optomechanics experiments like the generation of Schrödinger cat states [1] and entanglement of picogram drums [2] represent huge achievements in this pursuit, their scalability in terms of both mass and wave function expansion is limited quite simply by their material connection to the environment as a source of decoherence. Eliminating or minimizing this connection, with e.g. optically levitated nanoparticles [3] or milligram torsion pendula [4] should in principle yield higher environmental isolation with simultaneously higher degree of motional control. Since optically mediated entanglement is predicted to be fundamentally challenging for these systems [5], most efforts to generate macroscopic motional entanglement are focused on utilizing the Coulomb interaction which is relatively short-ranged ($\propto 1/r^3$).

In this work, we propose to use a conductive wire as a mediator of the particle-particle Coulomb interaction. This has been shown to enhance quantum protocols in the past [6]. Here, we are fully characterizing the effect of the wire with regards to extended range, tunability of the resulting force and added decoherence. We quantize the electromagnetic field in the presence of the lossy wire utilizing the formalism of macroscopic quantum electrodynamics [7]. Decoherence and coupling rates are extracted from a Born-Markov master equation and expressed in terms of the classical Green's function. Our treatment uncovers an unconventional coherent squeezing rate in the modified Hamiltonian, which enhances the entanglement generation and which counterintuitively increases with the resistance of the wire. We verify the extended range of the interaction using the Green's function for an infinitely extended wire and we determine parameter regimes in which entanglement can be experimentally observed for levitated nanoparticles, as well as milligram-scale torsion pendula.

References

- [1] Marius Bild et al. "Schrödinger cat states of a 16-microgram mechanical oscillator". In: *Science* 380.6642 (Apr. 21, 2023). Publisher: American Association for the Advancement of Science, pp. 274–278. DOI: 10.1126/science.adf7553.
- [2] Shlomi Kotler et al. "Direct observation of deterministic macroscopic entanglement". In: *Science* 372.6542 (May 7, 2021). Publisher: American Association for the Advancement of Science, pp. 622–625. DOI: 10.1126/science.abf2998.
- [3] C. Gonzalez-Ballester et al. "Levitodynamics: Levitation and control of microscopic objects in vacuum". In: *Science* 374.6564 (Oct. 8, 2021), eabg3027. DOI: 10.1126/science.abg3027. arXiv: 2111.05215[cond-mat, physics:physics, physics:quant-ph].
- [4] Sofia Agafonova et al. *Laser cooling a 1-milligram torsional pendulum to 240 microkelvins*. Aug. 18, 2024. arXiv: 2408.09445[quant-ph].
- [5] Henning Rudolph et al. "Quantum theory of non-Hermitian optical binding between nanoparticles". In: *Phys. Rev. A* 110.6 (Dec. 3, 2024). Publisher: American Physical Society, p. 063507. DOI: 10.1103/PhysRevA.110.063507.
- [6] Jorge R. Zurita-Sánchez and Carsten Henkel. "Wiring up single electron traps to perform quantum gates". In: *New Journal of Physics* 10.8 (2008). Publisher: IOP Publishing, p. 083021.
- [7] Stefan Yoshi Buhmann. *Dispersion Forces I: Macroscopic Quantum Electrodynamics and Ground-State Casimir, Casimir and van der Waals Forces*. Vol. 247. Springer Tracts in Modern Physics. Berlin, Heidelberg: Springer, 2012. DOI: 10.1007/978-3-642-32484-0.

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