Magnetically Levitated Systems Approaching the Quantum Regime

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Studying the boundary between quantum and classical physics in macroscopic systems is a central challenge in modern physics. In this context, levitated systems are becoming increasingly important because they provide excellent isolation and avoid clamping losses, enabling improved quantum control of mechanical motion compared to traditional micro- and nano-mechanical resonators. Beyond optical tweezers, magneto-levitated systems based on static superconducting traps that exploit the Meissner effect are particularly promising, as they operate at cryogenic temperatures and exhibit exceptional immunity to dissipative effects.

Achieving quantum superpositions of massive objects in magnetically levitated systems requires overcoming two major challenges: (i) explaining the ultimate mechanisms of friction in such systems, and (ii) cooling them to the quantum ground state.

To address the first issue, we have examined the dissipation arising from surface resistance due to the unavoidable presence of quasiparticles. At the extremely low (sub-gap) frequencies of interest, this dissipation does not stem from Cooper-pair breaking, but rather from the oscillatory, damped motion of quasiparticles at finite temperatures. Our goal is to establish an upper bound on the intrinsic dissipation of this class of levitated systems.

To address the second issue, we carried out a first proof-of-concept experiment in which we cooled the angular motion of a levitated micromagnet in a superconducting Meissner trap using magnetic feedback. We analyzed the experimental data with a theoretical model tailored to our feedback scheme. Starting from an operating temperature of a few kelvin, we cooled the system down to a few millikelvin. We also discuss how lower temperatures could be reached through improvements in the performance of the experimental apparatus.

Finally, I will discuss preliminary results from a theoretical study exploring the use of a machine-learning-based strategy (reinforcement learning) to enhance the feedback cooling process. This approach introduces an adaptive agent that controls the feedback in real time, with the ultimate goal of reaching the quantum regime of a massive levitated system.

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