Quantum Beam-Splitter Cooling and Thermometry in Large Trapped-Ion Crystals

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Synopsis We propose quantum beam-splitter cooling (QBSC), a protocol for rapid near-ground state cooling of the center-of-mass mode of a large trapped ion crystal via a red-sideband SWAP with the collective spin followed by a spin reset, and quantum beam-splitter thermometry (QBST), which is near-optimal. This work is available as a preprint on arXiv (arXiv:2606.21357) and is currently under review at Physical Review Applied.

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Laser cooling of trapped ions has enabled the exquisite control of single ions and Coulomb crystals of multiple ions for quantum science experiments. Experiments with long ion strings and two-dimensional trapped ion crystals carried out in the strong sideband coupling regime have observed many-body enhancements in the cooling rate of specific motional modes, suggesting that cooling in this regime cannot be treated as independent contributions from individual ions in the crystal.

We propose and characterize a protocol for rapid near-ground state cooling of the center-of-mass (c.m.) mode of a large trapped ion crystal. When the initial mean thermal occupation of the mode $\bar{n}_i$ is small compared to the number of ions N, a red sideband (RSB) drive implements a beam-splitter type SWAP operation between the mode and the collective spin of the N ions, with the latter effectively serving as a quantum harmonic oscillator. Subsequently, a reset of the spins removes the entropy, leading to near-ground state cooling of the c.m. mode. We term this protocol as quantum beam-splitter cooling (QBSC).

We analyze the impact of several practical imperfections on the final temperature achievable under QBSC, including finite ion number, off-resonant carrier and blue-sideband contributions, and the impact of the sideband drives arising from spectator modes. In addition, we outline practical strategies to eliminate the carrier drive.

Furthermore, we show that measuring the population statistics of the ions at the end of the SWAP operation can enable near-optimal quantum beam-splitter thermometry (QBST), with the classical Fisher information approaching the quantum Fisher information of a thermal state. We discuss the connection of QBSC with continuous sideband cooling and compare QBST with a recently proposed rapid adiabatic passage-based thermometry scheme.

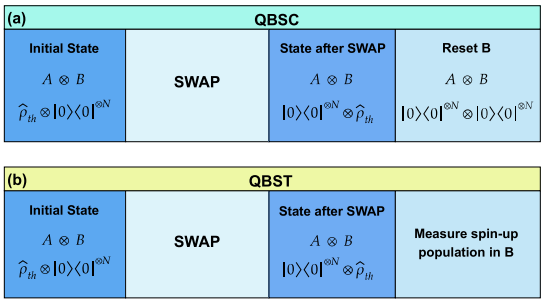

Figure 1. Schematic of the two QBS protocols (reproduced from Fig. 1 of Ref. [1])

Our work constitutes an example of harnessing many-body effects to open new routes to laser cooling and thermometry in large trapped ion crystals.

References

[1] Rajakumar K, Das A, Pandey A and Shankar A 2026 *arXiv:2606.21357* https://arxiv.org/abs/2606.21357

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