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Overcoming and harnessing non-commuting dynamics in trapped ions

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A trapped ion forms a hybrid system consisting of the electronic spin and bosonic motional modes. The Hamiltonian describing the interaction between laser light and this hybrid system, when containing only commuting terms, leads to simple dynamics. However, the presence of non-commuting terms, either due to spurious off-resonant interactions or deliberate inclusion, leads to complex and rich dynamics. We present two regimes for dealing with this complexity: either by suppressing the unintended non-commuting terms and recovering simpler dynamics or by harnessing the rich dynamics to realize previously experimentally unexplored interactions.

In the first regime, an off-resonant non-commuting term present in Mølmer–Sørensen two-qubit entangling gates causes an error that increases with the drive strength. This manifests as an effective speed limit of two-qubit entanglement via this method. However, using phase stabilized standing waves, we can suppress this non-commuting term and break this speed limit\[Saner, Bazavan et al. 2023\].

In the second regime, we generate non-linear bosonic interactions by combining non-commuting spin-motion couplings\[Sutherland et al. 2021\]. Using two interactions linear in the bosonic mode with non-commuting spin conditioning, we generate effective non-linear interactions with more favourable scaling than conventional techniques driving higher order sidebands\[Meekhof et al. 1996\]. To maintain the non-commuting relationship between the spin-components, we actively stabilize the optical phase of the driving fields. As such, we are able to demonstrate nth order non-linear interactions: squeezing, trisqueezing, and quadsqueezing\[Bazavan et al. 2024\], the latter of which we believe is the first experimental demonstration.

The common underlying physics, involving non-commuting terms, and the experimental requirements, such as the active stabilization of the optical phase in the driving fields, allow for the utilization and concurrent optimization of the same experimental apparatus, which we shall discuss.

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