Quantum Control of Motional States in Mixed-Species Trapped Ion Crystals



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Trapped ion motion states

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12 motion degrees of freedom





Worry about:

- Off resonant couplings
- Incomplete population transfer
- Debye-Waller effects
- Larger time-dilation shifts
- Gate errors from thermal motion
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Trapped ion motion states



C. Fluhmann, T. L. Nguyen, M. Marinel V. Negnevitsky, K. Mehta, J. P. Home, *Nature* **566**, 514 (2019)

The mode-coupling operation

Direct parametric coupling between two chosen modes via an electric potential



- D. J. Wineland and H. G. Dehmelt, Int. J. Mass Spectrosc. Ion Proc. 16 338 (1974)
- R. S. Van Dyck, Jr., P. B. Schwinberg, and H. Dehmelt, New Frontiers of High Energy Physics (book) (1978)
- D. J. Gorman et al., Phys. Rev. A, 89 062332 (2014)
- K. R. Brown et al., Nature 471, 196 (2011)



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Energy Physics (book) (1978)

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Mode coupling principle

In order to couple two modes OOPH and ALT, we need

Correct coupling frequency

□Correct coupling curvature

Generate
$$H_{coupling} = \hbar g(e^{i(\phi+\omega t)} \hat{a}_0^{\dagger} \hat{a}_A + e^{-i(\phi+\omega t)} \hat{a}_0^{\dagger} \hat{a}_A^{\dagger})$$

where $\omega = (\omega_0 - \omega_A)$
 ${}^{9}Be^{+.25}Mg^{+.9}Be^{+}$
Axial (z)
 $A(t)$
 $A(t)$
 $A(t)$
 $Difficult to couple due to filters
Out-of-Phase$



Axial (z) Difficult to couple due to filters Out-of-Phase (OOPH) Alternating (ALT) 3.66 MHz4 filters







Phase coherence of mode coupling





⁹Be⁺

²⁵Mg⁺

Application: Improving ground state cooling

arXiv.2308.05158

- Sometimes, not all modes are easily cooled by the coolant ion(s)
 - For example, weak cooling could result from ion participation or laser geometry constraints
- Solution: couple strongly cooled modes to weakly cooled modes



 $\Delta \vec{k}$

Application: Improving ground state cooling



Application: Improving ground state cooling



Application: repetitive measurement of motional states



Use the protected mode to perform repetitive readout of motion state through Mg⁺ without corruption from photon recoil.

Application: repetitive measurement of motional states Store the motion state in the



Demonstration of repeated measurement

 Objective: To distinguish between |0> and |1> of a motional state through repetitive measurement without corrupting the state of interest



Comparison with sideband measurements (N=1)

Exp



Comparison with sideband measurements (N=2)

Exp



Comparison with sideband measurements (N=3)

Exp



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Summary

Mode coupling and repeated detection arXiv.2205.14841 Cooling using mode coupling arXiv.2308.05158

- Using modulated voltages on an ion trap, two motional modes along any axes can be rapidly and coherently coupled.
 - Modulation needs to have the correct frequency and curvature in order for coupling to be successful.
- Modes that are weakly cooled can be coupled to modes that are strongly cooled to enable cooling of more modes without additional beamlines.
- In crystals that have a protected mode, repeated measurement of a motional mode is possible, enabling more avenues of exploration of motional degrees of freedom, or for continuous-variable QIP in ion traps.