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



P.-Y. Hou, S. D. Erickson, D. C. Cole, G. Zarantonello, A. D. Brandt, S. Geller, A. Kwiatkowski, S. Glancy, E. Knill, A. C. Wilson, D. H. Slichter, D. Leibfried

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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)

- D. J. Gorman et al., Phys. Rev. A, 89 062332 (2014)
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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

NIST Ion Storage Group

Giorgio Zarantonello

Graduate student and postdoctoral researcher positi Adamavailable! Dietrich Leibfried

Panyu

Hou

Andrew Wilson

Daniel

Slichter

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.