Coherent control of ground-state cooled ions in a Penning trap

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People involved in this work

- **PhD students**: Ollie Corfield, Jake Lishman (theory), Manoj Joshi (now at Innsbruck), Vincent Jarlaud, Pavel Hrmo (now at Innsbruck)
- **Staff**: Richard Thompson, Florian Mintert (theory), Danny Segal (1960-2015)
Outline of the talk

• Laser cooling in the Penning trap
• Effect of a large Lamb-Dicke parameter
• Sideband cooling of a single ion
  • Coherent superpositions of motional states
  • Coherent control with a bichromatic beam
  • Coherent manipulation of the motion in high-\( n \) states
• Sideband cooling of two-ion ‘crystals’
• Sideband cooling of the radial motion
• Outlook
Laser cooling in the Penning trap

- Doppler cooling is basically the same in radiofrequency and Penning traps, but...
- Zeeman splitting of levels requires multiple laser frequencies for cooling
  » Avoided in simple ions (Mg\(^+\) and Be\(^+\)) by using optical pumping techniques
- Magnetron motion has negative energy and is hard to cool
  » Needs laser beam offset from trap centre
  » Or additional fields (rotating wall, axialisation)
- Oscillation frequencies are relatively low (<1MHz in our case)
Working with calcium in a Penning trap

- In the magnetic field of the Penning trap we obtain large Zeeman splittings.
- We require 10 laser frequencies (4 lasers) for Doppler cooling.
- We can create and control 1, 2, and 3-D Coulomb crystals.

The 729 nm transition is the qubit transition.
**Sideband cooling: “trapped” motional states**

- The Lamb-Dicke parameter $\eta$ determines the amplitude of the motional sidebands
  \[ \eta = x_0(2\pi/\lambda) \sim 0.2 \text{ for our trap} \]
  $[x_0$ is size of g.s. wavefunction$]$

- The strength of each motional sideband depends on $\eta$
  - *Quantum equivalent to sidebands in classical frequency modulation*

- For our low trap frequencies we expect the first red sideband to have zero amplitude around $n=80$

- Cooling on the first red sideband (R1) will only be effective for $n<80$

- Around 20% of the population is at $n>80$ at the Doppler limit ($<n>=47$)
After sideband cooling on the first red sideband (R1):
- much of the population is in $n=0$
  - this gives the strong asymmetry between R1 and B1
- but some is trapped around $n=80$
  - This gives the higher order sidebands in the spectrum
Clearing out the “trapped” motional states

- Cooling on the first red sideband (R1) will only be effective for $n<80$
- Around 20% of the population is at $n>80$ at the Doppler limit
- To pump this population we need to drive the 2nd red sideband (R2) first
  - R2 is strong right up to $n=140$ but does not give effective cooling at low $n$
- The procedure is then
  - R1 (10 ms)
  - R2 (5 ms)
  - R1 (5 ms) at reduced power
Axial sideband cooling with multiple stages

Absence of red sideband indicates that ion is in the ground vibrational state.

Cooling sequence is R1 (10ms), R2 (5ms), R1 (5ms, reduced power)

\[ \langle n \rangle \sim \frac{\text{R1 amplitude}}{\text{B1 amplitude}} \]

Motional ground state occupation is >98%; heating rate <1 phonon/s
Superpositions of motional states

- $\pi/2$ pulse on the carrier (C)
- $\pi$ pulse on 1$^{st}$ red sideband (R1)
- Wait time $T$
- $\pi$ pulse on 1$^{st}$ red sideband (R1)
- $\pi/2$ pulse on the carrier (C)
- Measure ground state population

Motional Ramsey fringes after 50ms wait time
Motional coherence times up to ~1s observed
**“Triple slit” using motional states**

- “2/3 \( \pi \)” pulse on the carrier (\( C \))
- \( \pi/2 \) pulse on 1\(^{st} \) red sideband (\( R1 \))
- \( \pi \) pulse on 2\(^{nd} \) red sideband (\( R2 \))
- Wait time \( T \)
- Reverse the pulse sequence
- Measure ground state population

Motional interference fringes after wait times \( T=0 \) (blue) and \( T=30\text{ms} \) (gold)

This is analogous to an optical triple slit and can be used to study higher order coherence (see Jake Lishman’s poster)
Bichromatic drive

- Simultaneous driving on the first Red and Blue sidebands (R1 and B1) is equivalent to the position operator \( x \sim a + a^+ \), generating after time \( t \) the displacement operator:
  \[
  D(\alpha) = \exp(\alpha a - \alpha^* a^+) \quad \text{with} \quad |\alpha| = \eta \Omega t/z_0
  \]
- So we can generate a coherent state using a bichromatic drive

Rabi oscillations on B1 after a 150\(\mu\)s bichromatic pulse. The fitted value of \( \alpha \) is 1.73
Sideband heating on the blue sideband

- Sideband cooling on R1 drives us towards $n=0$
- After cooling to the ground state, we can also drive the ion on B1 back towards higher $n$ states
- This prepares an incoherent spread of population around the first minimum with $\Delta n \sim 10$
- After sideband heating, the spectrum shows a distinctive minimum for first order sidebands
Here we have driven the ion on B1 after sideband cooling in order to drive the population into the first minimum at $n=80$. 

**Spectrum of ions in the trapped state**
Coherence in highly excited motional states

- After sideband heating the population is centred in a narrow range of $n$ around a minimum.
- The strengths of the other sidebands are often fairly constant across the distribution.
- Therefore we see coherent behaviour.
- We can study the optical and motional coherence for high $n$ states by using $\pi/2$ pulses to create coherent superpositions of states.
- The interference persists because the other sideband strengths are fairly constant across the range of $n$ we populate.
Preparation of superposition of high-$n$ states

- A $\pi/2$ carrier pulse creates a coherent superposition of $|g,n\rangle$ and $|e,n\rangle$
Preparation of superposition of high-$n$ states

- A $\pi/2$ carrier pulse creates a coherent superposition of $|g,n\rangle$ and $|e,n\rangle$
- A $\pi/2$ B3 pulse then creates a coherent superposition of $|g,n\rangle$, $|g,n-3\rangle$, $|e,n\rangle$ and $|e,n+3\rangle$
- Period of free evolution $T$
- Probe the coherence with a second pair of pulses on B3 and carrier (with variable phases)
- Measured interference is (nearly) independent of $n$
Coherence measurements

- At small $T$ we see fringe visibility $\sim 1$
- After 1 ms the optical coherence is lost and the visibility drops to $\sim 0.5$
- Motional coherence is preserved out to $\sim 100$ ms for $\Delta n=3$
Sideband cooling of 2-ion crystals

- Two ions can arrange themselves along the axis or in the radial plane.
- In each case there are two axial oscillation modes.
- Axial crystal:
  - Centre of Mass at $\omega_z$
  - Breathing Mode at $\sqrt{3} \omega_z$
- Radial crystal:
  - Centre of Mass at $\omega_z$
  - Rocking between $\sqrt{\omega_z^2 - \omega_1^2}$ and $\omega_z$ depending on ion separation (where $\omega_1 = \sqrt{\omega_c^2/4 - \omega_z^2/2}$ is the effective radial trapping frequency).

Note that the ions are imaged from the side and the radial crystal is rotating due to the magnetic field.
Two-ion axial crystal after Doppler cooling

- The spectrum is complicated because each sideband of one motion has a complete set of sidebands due to the other motion.
- The overall width corresponds to the Doppler limit of ~ 0.5 mK.
Trapped motional states in 2D

- There are two independent axial modes
  - The strength of each sideband depends on both quantum numbers
- We have to use a combination of several different sidebands of each motion
- But there are still regions that are never pumped by pure centre of mass sidebands or pure breathing mode sidebands
  - We have to use “sidebands of sidebands” in the cooling sequence
Sideband cooling of two ions in axial crystal

- We have cooled both modes of the two-ion axial crystal
  - COM at $\omega_z$ and breathing mode at $\sqrt{3} \omega_z$
  - The final mean quantum numbers are $n_{\text{COM}}=0.3$ and $n_{\text{B}}=0.07$
  - Heating rates are also low

https://arxiv.org/abs/1705.08518
Axial sideband cooling of two-ion radial crystal

- The ions are both in the radial plane
- We see artifacts due to the rotational motion in the radial plane
- The two axial modes frequencies cannot be resolved in this plot
  - This makes the cooling process more straightforward as both cool together
- We also have cooling results for up to 10-ion radial crystals
Radial motion of a single ion

- The radial motion in the Penning trap has two modes
  - Cyclotron motion (fast) [700kHz]
  - Magnetron motion (slow) [10s of kHz]
- The sideband spectrum will show structure due to both motions
- We use the spectrum to measure the temperatures of the two modes directly from the velocity distribution
Radial spectrum at low potential

- The (fast) cyclotron motion gives rise to sidebands.
- The ~4 MHz FWHM corresponds to a cyclotron temperature of ~7 mK.
- Each cyclotron sideband has structure due to the magnetron motion.
  - but individual sidebands are not resolved here.

The narrow width of the magnetron structure demonstrates that its "temperature" is very low (~40 μK).

See Mavadia et al
Phys. Rev. A 89, 032502
Problems for radial cooling

- Need to cool two modes at the same time
  - We have gained experience of this with ion crystals

- The magnetron sidebands are unresolved
  - Increase trap voltage to raise magnetron frequency

- The magnetron energy is negative
  - Cool on the blue sidebands of magnetron motion, not red

- The initial quantum number of magnetron motion is very large (\(n\) up to 1000 in some cases after Doppler cooling)
  - Use the axialisation technique to couple to cyclotron motion
Axialisation

- This technique is used in the mass spectrometry field to couple the magnetron motion to the cyclotron motion for cooling
- We have adapted it for use with optical sideband cooling
- The ion is driven by an oscillating radial quadrupole field at $\omega_c = eB/M$

**Classically:**

The field creates a coupled oscillator system so there is a continuous transfer of energy between the two modes. Damping of both comes from the strong cyclotron cooling. Eventually $r_m \approx r_c$

**Quantum Mechanically:**

The field drives transitions where $n_m = -1$ and $n_c = +1$. The Doppler cooling continuously drives $n_c$ to lower values. Eventually $n_m \approx n_c$
The carrier is very strong to bring out the other sidebands.

The asymmetry in cyclotron sidebands indicates $n_c=0.07\pm0.03$.

The (reversed) asymmetry in the magnetron sidebands indicates $n_m=0.40\pm0.06$.

Weak second-order sidebands can also be seen.
Summary

- We have cooled the axial motion of single ions and small Coulomb crystals to the ground state in a Penning trap.
- Coherent processes can be observed even at high motional quantum numbers for single ions.
- We have performed the first sideband cooling of the radial motion of an ion.

Thank you for your attention!
Heating rate comparison

![Graph showing the comparison of heating rates with various data points and labels for different researchers such as Turchette, DesLauriers, Diedrich, Lucas, Roos, Schulz, Stick, Poulsen, Benhelm, Blakestad, DeVoe, Monroe, Tamm, and This work. The x-axis represents electrode distance (µm) ranging from 50 to 10,000, and the y-axis represents scaled field noise $S_E(\omega)$ ranging from $10^{-10}$ to $10^0$. The graph includes a linear trend line with data points scattered across the plot.](image-url)
We can see Rabi oscillations for ground-state cooled ions

- The carrier Rabi frequency is up to 60 kHz and the coherence time is ~0.8 ms
- Spin-echo techniques can be used to increase coherence time to a few ms
Ramsey interference with two-ion crystal

Ramsey interference pattern after 140μs delay between two $\pi/2$ pulses

- The observation of Ramsey fringes confirms coherent behaviour of the system
Heating rate results

- The heating rate averages at around 0.4 phonons/second and is roughly independent of frequency
  - Probably limited by technical noise
- The heating rate is expected to be low because
  - The trap is very large (radius 10 mm)
  - The trapping fields are static and there is no micromotion

This heating rate was taken at an axial frequency of 200 kHz

Goodwin et al. PRL 2016
Cooling effect of the sequence of sidebands

- This shows the combined effect of a sequence of 5 different sidebands including one “sideband of a sideband”
- Every region of the plane is now addressed by at least one of the sidebands effectively
- We cycle through this sequence of sidebands many times to complete the cooling process
Figure 6.4: Plot showing fraction of population at the Doppler limit that lies above the lowest coupling minima of the first two red sidebands as a function of the trapping frequency.
Ramsey fringes

\[ T_w = 700\mu s, \ \Omega_0/2\pi = 3.2 \text{ kHz} \]