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Sympathetic cooling of trapped Cd^+ isotopes

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We sympathetically cool a trapped $^{112}Cd^+$ ion by directly Doppler cooling a $^{114}Cd^+$ ion in the same trap. This is the first demonstration of optically addressing a single trapped ion being sympathetically cooled by a different species ion. Notably, the experiment uses a single laser source, and does not require strong focusing. This paves the way toward reducing decoherence in an ion trap quantum computer based on Cd^+ isotopes.

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A collection of cold trapped ions offers one of the most promising avenues towards realizing a quantum computer [1–4]. Quantum information is stored in the internal states of individual trapped ions, while entangling quantum logic gates are implemented via a collective quantized mode of motion of the ion crystal. The internal qubit states can have extremely long coherence times [5], but decoherence of the motion of the ion crystal may limit quantum logic gate fidelity [6]. Furthermore, when ions are nonadiabatically shuttled between different trapping regions for large-scale quantum computer schemes [4,7], their motion must be recooled for subsequent logic operations.

Direct laser cooling of the qubit ions is not generally possible without disturbing coherence of the internal qubit states. Instead, additional "refrigerator" ions in the crystal can be directly laser cooled, with the qubit ions cooled in sympathy by virtue of their Coulomb-coupled motion [8]. The laser cooling of the refrigerator ions can quench unwanted motion of the ion crystal, while not affecting the internal states of the qubit ions [4,9,10]. Sympathetic cooling has been observed in large ensembles of ions in Penning traps [8,11], impurities in small collections of ion crystals, and in small ion crystals consisting of a single species, where strong laser focusing was required to access a particular ion without affecting the others [12]. Here, we report the first demonstration of sympathetic cooling in a small ion crystal with two different species where both species are independently optically addressed.

We study sympathetic cooling of individual Cd^+ isotopes confined in a rf trap. One ion isotope (the refrigerator ion) is continuously Doppler-cooled by a laser beam red detuned from its D2 line ($S_{1/2}$-$P_{3/2}$), while the other isotope (the probe ion) is either Doppler cooled or Doppler heated by another beam, whose frequency is scanned around its D2 resonance line. The effect of the sympathetic cooling is to enable measuring fluorescence on the blue side of the probe ion's resonance. Ordinarily, when the probe laser beam is tuned to the blue of the probe ion's resonance, the ion ceases fluorescing due to Doppler heating, but the sympathetic cooling from the refrigerator ion keeps the probe ion cold and fluorescing regardless of the probe tuning.

In the experiment, the probe ion is $^{112}Cd^+$, while the refrigerator ion is $^{114}Cd^+$ (both isotopes have zero nuclear spin). The respective D2 lines of these two neighboring isotopes are separated by about 680 MHz, with the heavier ion at lower frequency, and the natural linewidth of each ion's excited $P_{3/2}$ state is $\gamma/2\pi \simeq 47$ MHz.

The experimental apparatus is schematically shown in Fig. 1. The Cd^+ D2 line resonant light near 214.5 nm is generated by quadrupling a Ti:sapphire laser. The laser is stabilized to a molecular tellurium feature near 429 nm to better than 1 MHz. The quadrupled UV output is split into two parts; one part is upshifted by $\sim$420 MHz, while the

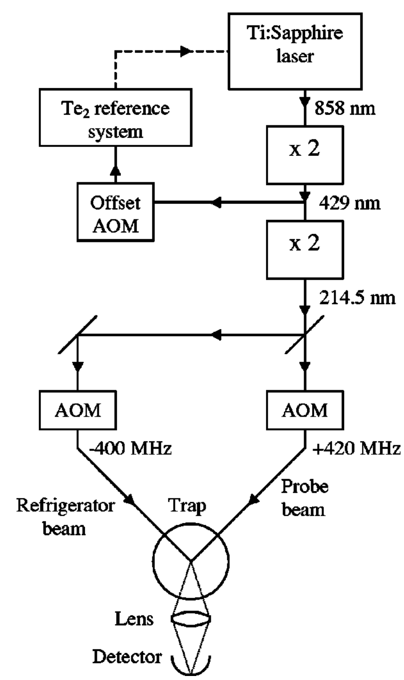

FIG. 1. Schematic diagram of the experiment. The 858 nm light from the Ti:sapphire laser is frequency doubled, then a small portion ($\sim$20 mW) of the 429 nm light is diverted to a tellurium-saturated absorption spectrometer. The double-pass acousto-optic modulator (AOM) in the Te_2 reference system allows tuning the Ti:sapphire beam frequency by about $\pm$25 MHz while locked. The remaining ($\sim$200 mW) portion of the 429 nm light is again frequency doubled to $\sim$15 mW of 214.5 nm radiation. The UV beam is then split into two parts, each of which is frequency-shifted by AOMs and directed into the trap.

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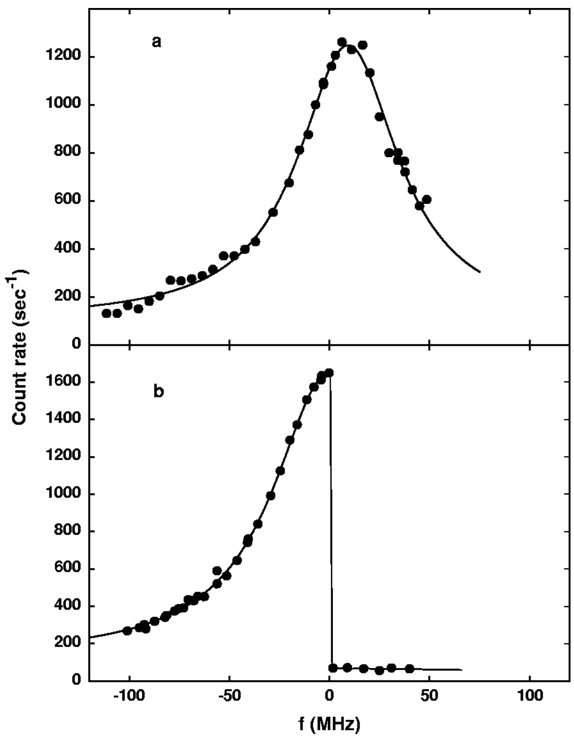

FIG. 2. UV fluorescence count rate from the $^{112}Cd^{+}$ probe ion (a) with and (b) without sympathetic cooling, plotted against the probe beam frequency detuning from resonance. Solid lines represent fits to the data using (a) a Voigt profile and (b) a Voigt shape for the below-resonance part of the data and a straight line for the above-resonance part of the data. The upper resonance line is shifted about 10 MHz blue of the lower resonance line, consistent with the expected ac Stark shift of the $^{112}Cd^{+}$ levels due to the off-resonant $^{114}Cd^{+}$ cooling radiation.

other is downshifted by $\sim$400 MHz using acousto-optical frequency shifters. The two beams are then directed into the ion trap through separate windows. Both beams uniformly illuminate the ion crystal in the trap. The upshifted UV beam (the probe beam) is scanned in frequency around the $^{112}Cd^{+}$ ion's D2 line, while the downshifted UV beam (the refrigerator beam) frequency is always kept to the red of the $^{114}Cd^{+}$ ion's D2 line. The UV fluorescence from the ions is collected by an f/5.6 lens and imaged onto a microchannel plate detector. The fluorescence counts are integrated for 10 s for each data point in a frequency scan.

We use an asymmetric quadrupole rf ion trap [13] with the electrode radius of about 200 microns. The trap's rf is $\Omega/2\pi \simeq 38.8$ MHz, the rf potential amplitude is about 200 V, and the trap's electrodes are kept at the same static potential. The measured secular trap frequency along the ions' separation axis is $\omega_x/2\pi \sim 2.8$ MHz.

To study sympathetic cooling, we load a $^{112}Cd^{+}$ ion and a $^{114}Cd^{+}$ ion into the trap by directing $\sim$1 mW of UV radiation focused to under 20 μm onto the trap electrodes, which have been previously coated with neutral cadmium. Presumably, the UV radiation ablates cadmium from the electrodes in ionic form. Due to the high abundance of isotopes 112 and 114 in natural cadmium (24% and 29%, respectively), loading the proper two isotopes is not unlikely. Typical trapping

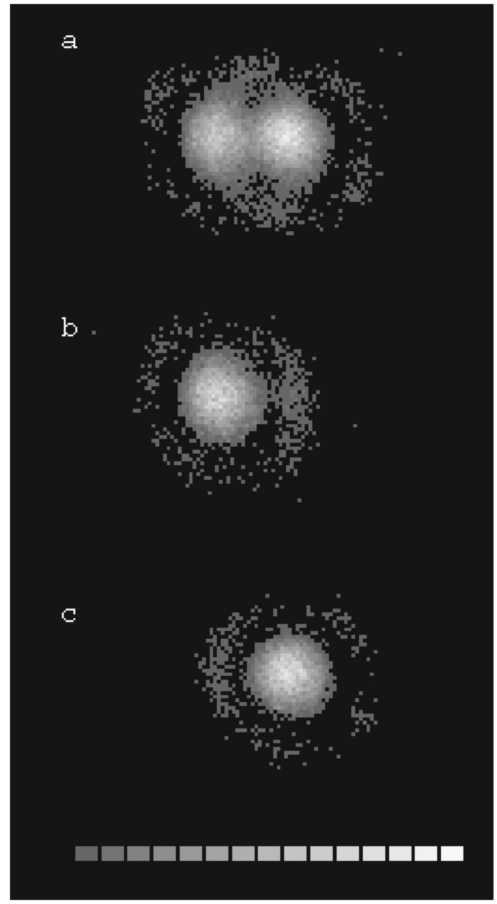

FIG. 3. Images of the $^{112}Cd^{+}$ and $^{114}Cd^{+}$ ions while illuminated by (a) both the refrigerator and the probe beam, (b) only the probe beam, and (c) only the refrigerator beam. The $^{112}Cd^{+}$ ion is on the left, while the $^{114}Cd^{+}$ ion is on the right. The two ions are separated by $\sim$2 μm. Note very faint images of the $^{114}Cd^{+}$ ion in (b) and the $^{112}Cd^{+}$ ion in (c) from the residual fluorescence from the far-detuned beams, partially obscured in this picture by the Airy rings. The below scale is linear in the integrated photon counts. The exposure time is 10 s for each picture.

times of the ions are greater than 1 hour, apparently limited by the interaction between the UV beam edges and the trap electrode surfaces. We estimate that the background pressure is about 10^{-11} torr. We set the trap's compensating electrode voltages such that the $^{112}Cd^{+}$ (probe) ion is near the rf null of the trap to minimize its micromotion and thus simplify its line shape [14].

In Fig. 2 the fluorescence from the $^{112}Cd^{+}$ ion is plotted against the probe beam frequency. In Fig. 2(a) both the probe and the refrigerator laser beams are on, while for the data in Fig. 2(b) the refrigerator beam is turned off. Note the telltale drop in fluorescence as the probe beam is tuned to the blue side of the $^{112}Cd^{+}$ resonance line in Fig. 2(b) caused by Doppler heating. On the other hand, the fluorescence curve in Fig. 2(a) is symmetric, which demonstrates that the $^{112}Cd^{+}$ ion is sympathetically cooled by the $^{114}Cd^{+}$ ion even as the probe beam is tuned to the blue of the resonance.

Images of the two ions at different lighting conditions are shown in Fig. 3; the probe ion ($^{112}Cd^{+}$) is on the left, while

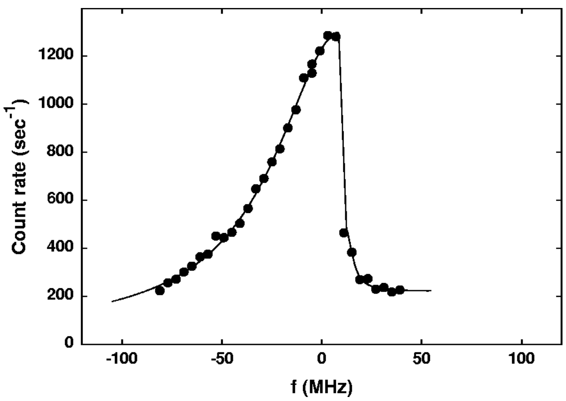

FIG. 4. UV fluorescence from a single $^{112}Cd^+$ ion while illuminated by both the refrigerator and the probe beam plotted against the probe beam frequency detuning from the resonance. The solid line is a Voigt fit to the data below the resonance and a hand-drawn line above the resonance.

the refrigerator ion ($^{114}Cd^+$) is to the right. Both the probe and the refrigerator beams are turned on for Fig. 3(a) in Fig. 3(b) only the probe beam is on, while in Fig. 3(c) only the refrigerator beam is on. Note very faint images of the $^{114}Cd^+$ ion in Fig. 3(b) and the $^{112}Cd^+$ ion in Fig. 3(c) from the residual fluorescence from the far-detuned beams.

For the data shown in Figs. 2 and 3, the probe beam intensity is $I_{probe} = 0.35 I_{sat}$, while the refrigerator beam intensity is $I_{ref} = 12 I_{sat}$, where the saturation intensity $I_{sat} \simeq 0.6$ W/cm^2. Such high refrigerator beam intensity is necessary because of the large amount of refrigerator ion micromotion. This significantly Doppler broadens the refrigerator ion line shape and makes cooling less efficient [15] than the comparable cooling/heating of the probe ion, which experiences little micromotion. The approximately 10 MHz shift of the probe ion resonance line in Fig. 2(a) compared to Fig. 2(b) is consistent with the ac Stark shift from the off-resonant refrigerator beam.

To demonstrate that the cooling seen in Fig. 2(a) is not caused by directly Doppler cooling the $^{112}Cd^+$ probe ion by the refrigerator beam (which indeed is red detuned from the $^{112}Cd^+$ ion's D2 line) we load a single $^{112}Cd^+$ ion into the trap, while shining both the refrigerator and the probe beams onto the ion. The curve in Fig. 4 shows the resulting fluorescence as a function of the probe laser frequency. When tuned to the blue of the resonance, the ion's fluorescence quickly drops to zero, indicating that the ion is heated by the probe beam; the direct Doppler cooling by the far-detuned refrigerator beam is not sufficient to keep the ion cold.

While the current experiment only investigates Doppler cooling, quantum logic gates with trapped ions generally require cooling to the Lamb-Dicke limit, where the ion's spatial extent is much smaller than the optical coupling wavelength. A similar setup should enable sympathetic cooling of Cd^+ isotopes to the Lamb-Dicke limit using stimulated-Raman sideband cooling [16], polarization-gradient (Sisyphus) cooling [17], or cooling using electromagneticallly induced transparency [18].

Ultimately, we plan to sympathetically cool $^{111}Cd^+$ qubits (nuclear spin-1/2) with $^{116}Cd^+$ refrigerator ions. The isotope shift between Cd^+ isotopes 111 and 116 is $\Delta/2\pi \simeq 5.2$ GHz. Below, we estimate the decoherence of a $^{111}Cd^+$ qubit under the influence of $^{116}Cd^+$ cooling radiation, assuming a background heating source is quenched by sideband cooling in the Lamb-Dicke limit. The photon scatter rate by the $^{116}Cd^+$ refrigerator ion $\Gamma_s \simeq (I/I_{sat})\gamma/2$ sets an upper limit on the cooling rate, which itself must be at least as large as the heating rate $\dot{n}$ for useful sympathetic cooling. The off-resonant spontaneous emission rate of the $^{111}Cd^+$ qubit ion is then of order $\Gamma_{qubit} \simeq \dot{n}(\gamma^2/4\Delta^2) \simeq 0.02$/sec for a heating rate of $\dot{n} \simeq 10^3$/sec [6]. Under the same conditions, the ac Stark shift of the $^{111}Cd^+$ qubit ion is $\delta_{AC}/2\pi \simeq (\dot{n}/2\pi)(\gamma/4\Delta) \simeq 0.3$ Hz, and only the fluctuations of this already small shift will cause decoherence. A similar analysis can be given for other methods of cooling. We find that the 5.2 GHz isotope shift appears large enough to comfortably neglect qubit decoherence from spontaneous emission and ac Stark shifts, while it is small enough so that optical modulators can provide the cooling radiation without the need for additional laser sources.

In summary, we have sympathetically cooled a single trapped $^{112}Cd^+$ ion through Doppler cooling of a neighboring $^{114}Cd^+$ ion. This is the first demonstration of optically addressing a single trapped ion being sympathetically cooled by an ion of a different species. The sympathetic cooling of multiple ion species is an important step toward scaling the trapped ion quantum computer, as it can reduce decoherence associated with unwanted motion of trapped ions, while preserving the internal qubit coherence. The Cd^+ system is convenient, as the sympathetic cooling can be accomplished without extra lasers and without strong focusing.

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