Laser Cooling to the Zero-Point Energy of Motion

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A single trapped $^{198}Hg^+$ ion was cooled by scattering laser radiation that was tuned to the resolved lower motional sideband of the narrow $^2S_{1/2}$-$^2D_{5/2}$ transition. The different absorption strengths on the upper and lower sidebands after cooling indicated that the ion was in the ground state of its confining well approximately 95% of the time.

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The subject of laser cooling of ions and neutral atoms is currently of great experimental and theoretical interest.[1] It has been applied to high-resolution spectroscopy, low-energy collisions, quantum jumps, and photon antibunching.[2] In all cooling experiments done so far, the oscillation frequency ω_v of the particle in its confining well was less than the linewidth Γ of the cooling transition. This condition also applies to free-atom experiments, where $\omega_v \rightarrow 0$. The lowest temperatures T have been obtained in recent free-atom experiments,[3,4] where kinetic energies near or below that corresponding to the recoil of a single photon from an atom at rest have been achieved ($T \approx 1$ μK). In this Letter we report, for the first time, laser cooling of a single bound atom in the resolved sideband regime $\Gamma \ll \omega_v$. An ion has been cooled so that it occupies the ground state of its confining potential most of the time.

The idea of laser cooling in the resolved sideband regime is as follows[5]: Let the rest frequency of the atom's cooling transition be ω_0. If the atom oscillates at frequency ω_v in its confining well, the atom's absorption and emission spectrum (as viewed in the laboratory) has resolved components at ω_0 and $\omega_0 \pm m\omega_v$ (m an integer). If we irradiate the atom with narrow-band radiation tuned to the first lower sideband at $\omega_0 - \omega_v$, the atom absorbs photons of frequency $\hbar(\omega_0 - \omega_v)$ and reemits photons of average energy $\hbar\omega_0$. Hence, on the average, each scattered photon reduces the atom's vibrational energy by $\hbar\omega_v$, or reduces the atom's vibrational quantum number n_v by 1. In this way, we can obtain $\langle n_v \rangle \ll 1$ and have the atom most of its time in the ground-state level of its confining potential.[6-8] When $\langle n_v \rangle \ll 1$, T is no longer proportional to $\langle n_v \rangle$ but depends logarithmically[7,8] on $\langle n_v \rangle$. The technique of sideband cooling has previously been applied to cool the magnetron motion of trapped electrons with an rf electronic excitation of the axial motion that was coupled to a cooled resistor.[9] The final temperature in this experiment was limited by thermal excitation and the energy of the magnetron motion corresponded to $\langle n_v \rangle \gg 1$. In the experiments described here, we achieve $\langle n_v \rangle \ll 1$ by optical sideband cooling. For our value of ω_v, T was about 50 μK. However, to the extent that the particle is in the ground state of its confining potential (about 95% of the time here) the fundamental limit of laser cooling for a confined particle has been reached.

Our experiments were performed with a single $^{198}Hg^+$ ion stored in a Paul (rf) trap[10,11] which had $\omega_v/2\pi = 2.96$ MHz (see Fig. 1). In order to optimize the cooling, a two-stage process[8] was used. First, the ion was cooled to near the Doppler cooling limit[1] ($T = \hbar\Gamma/2k_B$, where k_B is the Boltzmann constant) by scattering light of wavelength 194 nm on the strong $^2S_{1/2}$-$^2P_{1/2}$ transition [(A) in Fig. 1(a)].[12] At the Doppler cooling limit, $\langle n_v \rangle \approx 12$ ($T \simeq 1.7$ mK) for each degree of freedom.[8] In the next stage of cooling, the 194-nm radiation was turned off and the narrow $^2S_{1/2}$-$^2D_{5/2}$ electric quadrupole transition [(B) in Fig. 1 (a)] was driven on the first lower sideband frequency $\omega_0 - \omega_v$. Since the natural lifetime of the $^2D_{5/2}$ state limits the maximum scatter rate to approximately $\frac{1}{2}\Gamma(^2D_{5/2}) \approx 6$ photons/s,[10,13] a cooling time of at least 6 s is required to reach $\langle n_v \rangle \simeq 0$ for all degrees of freedom. This time becomes even longer, or cooling is prevented, if external heating is present. Therefore, in order to enhance the sideband cooling rate, the lifetime of the $^2D_{5/2}$ state was shortened by coupling it to the fast decaying $^2P_{3/2}$ state by 398-nm radiation [(C) in Fig. 1(a)]. From the $^2P_{3/2}$ state, the ion has high probability

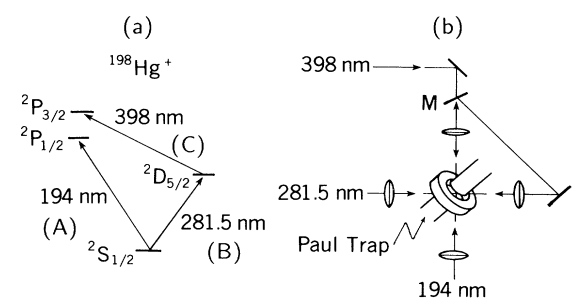

FIG. 1. (a) A simplified energy level scheme of Hg II showing the optical transitions involved in our sideband cooling experiment. (b) The geometrical arrangement of the laser beams. The 194-nm fluorescence is detected normal to the plane of the figure. Mirror M reflects 194-nm radiation while transmitting 398-nm radiation.

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of rapidly decaying to the ground state. When $\langle n_v \rangle \ll 1$, a quantitative measurement of $\langle n_v \rangle$ from the absorption spectrum becomes very simple. The strength of absorption S_L on the lower sideband is proportional to $\langle n_v \rangle$, while the strength S_U of the upper sideband is proportional to $\langle n_v \rangle + 1$.[8] When $\langle n_v \rangle$ approaches zero, the lower sideband disappears because no more vibrational quanta can be extracted from the ion. If the sideband absorption spectrum is probed with saturating power, the ratio of the strengths of lower to upper sidebands becomes independent of power[14] and directly gives $\langle n_v \rangle$.

To simplify our discussion, we have assumed the trap states and associated wave functions are those of a harmonic potential which is equal to the classical pseudopotential of the rf trap. In the quantum treatment of the rf trap,[15,16] the relevant states are not energy eigenstates because of the time dependence of the potential. However, when the trap drive frequency $\Omega \gg \omega_v$, the atom's optical spectrum and transition matrix elements relevant for cooling closely approximate those for a harmonic potential equal to the classical pseudopotential. The states which represent the cooled ion look like harmonic-oscillator states whose dimensions oscillate with small amplitude at frequency Ω. These states are of the form $\exp[-i\omega_v(n+\frac{1}{2})t]f_n(x,t)$ where the f_n are periodic in time with period $2\pi/\Omega$.[16]

Our trap[10,11] ($r_0 \simeq 466$ μm, $z_0 \simeq 330$ μm) was operated at a trapping field frequency $\Omega/2\pi = 23.189$ MHz. With an rf peak voltage amplitude $V_0 \approx 1.2$ kV and a static potential $U_0 = +71.4$ V applied to the ring electrode, the trap potential was approximately spherical. In order to cool all motional degrees of freedom to near the Doppler cooling limit for the (A) transition, two orthogonal beams of 194-nm radiation, both at an angle of 55° with respect to the trap symmetry (z) axis, were used (Fig. 1). The radiation to drive the (B) transition was derived from a frequency stabilized dye laser ($\lambda = 563$ nm) with a linewidth less than 20 kHz. The output radiation from this narrow-band laser was frequency doubled and focused to as much as 25 W/cm^2 at the position of the ion; this allows strong saturation on the cooling transition. The radiation to drive the (C) transition was derived from a frequency stabilized LD 700 dye laser whose output radiation was frequency doubled and focused to give approximately 1 mW/cm^2 at the position of the ion.

Before the sideband cooling experiment was started, an absorption spectrum of the (B) transition was taken[17] to determine the carrier frequency as well as the sideband frequencies (inset Fig. 2). We made sure that the 282-nm source had equal power at both the upper and lower sideband frequencies. For the sideband cooling and the probing of the absorption spectrum, the following computer-controlled sequence was run repeatedly. First, the 398- and 194-nm radiation were turned on simultaneously for a 20-ms interrogation period. If the 194-nm fluorescence exceeded a preset value during this

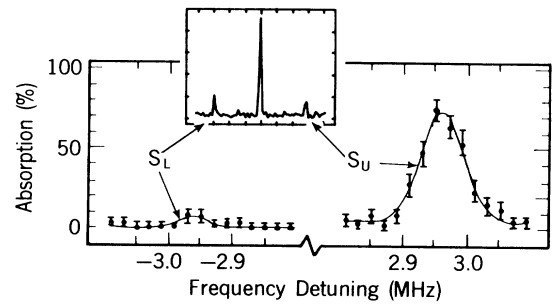

FIG. 2. Absorption spectrum of the $^2S_{1/2}$-$^2D_{5/2}$ electric quadruple transition of $^{198}Hg^+$. The inset spectrum was taken before sideband cooling was applied. It shows the carrier at zero detuning (frequency ω_0) and the first sidebands (at frequencies $\omega_0 - \omega_v$ and $\omega_0 + \omega_v$) generated by the ion's motion in the approximately spherical well. For this spectrum, the bandwidth of the 282-nm radiation was broadened to 120 kHz to reduce the number of required data points and the laser power was reduced in order to avoid saturation. The enlarged part of the figure shows the absorption strength S_L (S_U) on the lower (upper) motional sideband 15 ms after the end of the sideband cooling. Values for S_L and S_U were obtained from Gaussian fits to the data points which are averaged over 41 sweeps.

period, it could be assumed that the ion was laser cooled and cycling between the $^2S_{1/2}$ and the $^2P_{1/2}$ states. This 20-ms interrogation period was repeated until this condition was satisfied. Then the 194-nm radiation was switched off and the 282-nm radiation, tuned to the first lower sideband at $\omega_0 - \omega_v$, was switched on for a cooling time τ_c (typically 200–500 ms). After the 282-nm radiation was switched off, the 398-nm radiation was kept on for a relaxation time τ_r (typically 5 ms) in order to empty the $^2D_{5/2}$ state. After this, the cooled ion was in the electronic ground state and the probing of the absorption spectrum was done as follows: The 282-nm source was switched on at saturating intensity for 10 ms at a frequency corresponding to one point near the upper or lower sideband frequency. After this, the 282-nm beam was switched off and the 194-nm radiation was switched on to see if the ion had made the transition to the $^2D_{5/2}$ state.[11] The result was averaged with the results of previous measurements at the same probe frequency. The frequency of the 282-nm source was stepped to the next value and the cooling and probing cycle was repeated until about 40 cycles for each value of the probe frequency were completed. The results of a typical run are shown in Fig. 2.

In order to deduce $\langle n_v \rangle$ for the different motional degrees of freedom, the geometry of our experiment (Fig. 1) has to be considered. The 282-nm beam enters the trap at an angle of 55° with respect to the z axis. The x and y directions were previously determined by the fixed spatial alignment of two simultaneously stored ions,[17] which we take to be along the x axis. From these data, the squares of the projections p_i of unit vectors along the

trap axes onto the 282-nm beam axis are calculated to be $p_x^2=0.03$, $p_y^2=0.64$, and $p_z^2=0.33$. Since we make the differences between the x, y, and z frequencies bigger than $1/\tau_c$, all directions are cooled simultaneously.[8] However, in the analysis, we assume that the probing absorption strength is due only to the ion's motion in the y and z directions. Since the x axis is nearly perpendicular to the 282-nm beam, no meaningful statement abut the energy in this degree of freedom can be made. By neglecting the contribution of the x motion to the sideband strength we overestimate $\langle n_v \rangle$ for the y and z directions. In order to deduce $\langle n_v \rangle$ for the y and z oscillations from our data (Fig. 2), an assumption about the energy distribution between the two directions has to be made. If we assume temperature equilibrium between the y and z degrees of freedom, both contain an energy corresponding to $\langle n_v \rangle = (1-S_L/S_U)^{-1/2}-1=0.051\pm0.012$ quanta. Therefore, for the y and z degrees of freedom, the ion is in the $n_v=0$ state 95% of the time. The corresponding temperature given by[8] $k_BT=\hbar\omega_v/\ln(1+1/\langle n_v \rangle)$ is $T=47\pm3$ μK. For any other energy partition, $\langle n_v \rangle$ and T for one degree of freedom would be less than these values. Independent of the energy distribution, for both degrees of freedom the temperature is much lower than the 194-nm Doppler cooling limit and the ion spends most of its time in the harmonic-oscillator ground-state level.

The theoretical sideband cooling limit[8] gives a value of $\langle n_v \rangle \approx 10^{-6}$. However, since the probing in the experiment is done at saturating power, the measured $\langle n_v \rangle$ corresponds to the energy of the ion at the end of the probing interval, which is typically 15 ms after the end of the sideband cooling, and external heating might have occurred. In order to check for external heating processes, we extended τ_r up to 100 ms and measured S_L/S_U as a function of τ_r. We determined a heating rate (due apparently to pickup of stray noise fields at radio frequencies) of $\langle \dot{n}_v \rangle \approx 6$/s. If we assume the heating is due to thermalization of the ion to room temperature by noise at frequency ω_v, the heating time constant is 95 h.[18] This rate varied slightly with ω_v around $\omega_v=3$ MHz, but was substantially higher for $\omega_v \lesssim 2.5$ MHz. From these heating data, the measured $\langle n_v \rangle$ is consistent with the theoretical limit at the end of the sideband cooling period. We also measured $\langle n_v \rangle$ for a single degree of freedom directly by changing U_0 to -25 V in order to split the radial and axial sideband frequencies. The 282-nm radiation was tuned so that only the first axial sideband at $\omega_v/2\pi=4.66$ MHz was cooled and probed. From the results, shown in Fig. 3, we calculate $\langle n_v \rangle = 0.049\pm0.045$ at the end of the cooling period, consistent with the theoretical cooling limit. The confinement of the axial motion is given by the spread of the zero-point wave function $z(\text{rms}) \approx 2.4$ nm.

For our data, the uncertainty in the second-order Doppler shift is dominated by the uncertainty in $\langle n_v \rangle$ and amounts to $\Delta\nu/\nu < 10^{-20}$ (Ref. 8). It can be made substantially lower by adiabatically lowering the potential well depth after the ion is cooled into the ground state. With our experiment, the absorption of a single quantum of energy at a (tunable) frequency in the MHz range can be detected with an efficiency of nearly 100%. With appropriate coupling to the ion's motion (for example, via one of the endcaps), a similar apparatus could serve as a very sensitive spectrum analyzer. In another possible application, the motion of a trapped charged particle could be damped by coupling it electronically[19] to a second laser-cooled ion in a separate trap, thereby reducing the first charged particle's kinetic energy to near the zero-point energy. Resonant excitation of the first particle's motion could then be detected very sensitively by its influence on the laser-cooled ion. Such a device might be useful in mass spectroscopy.

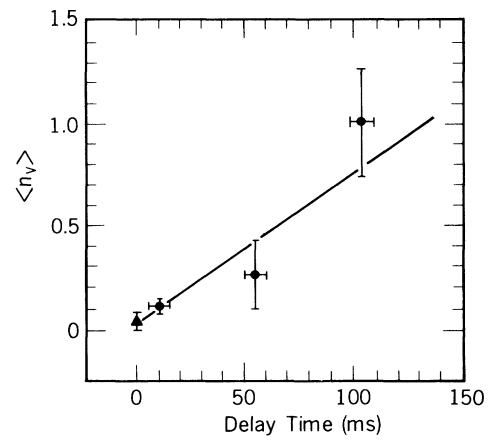

FIG. 3. Vibrational quantum number $\langle n_v \rangle$ for the axial motion ($\omega_v/2\pi=4.66$ MHz) as a function of time delay between the end of the sideband cooling and probing. A linear extrapolation of the data points (circles) to zero delay time yields $\langle n_v \rangle$ (triangle) consistent with the theoretical expectation.

In summary, we have realized laser cooling in the resolved sideband regime for the first time. The kinetic energy of a trapped atomic ion was reduced to a value where it spent most of its time in the ground-state level of its confining well. To the extent that the ion is in the zero-point energy state of motion, this realizes for the first time the fundamental limit of laser cooling for a bound particle and the ideal of an isolated atomic particle at rest to within the quantum-mechanical limits imposed by the surrounding apparatus.

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[18]The quantity actually measured is the probability, after a time τ_r, of finding the ion in a state with quantum number n_v, where $1 \leq n_v \leq n^* \simeq 10^4$. Strong, discontinuous heating, such as collisions with neutral atoms, would result in $n_v \gg 1$ after each heating event. Hence, a measurement of S_L/S_U vs τ_r would yield a heating rate lower than the actual one. In contrast, a continuous heating process, such as rf noise, would cause $\langle n_v \rangle$ to increase smoothly with time, and the analysis should be valid.

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