Hg^+ Single Ion Spectroscopy*

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Introduction

A single ion in an electromagnetic trap can be localized in a small volume and held for a long period of time. A trapped ion also can be isolated from collisions and other perturbations and laser cooled to low temperatures. By monitoring the presence or absence of fluorescence from a strongly allowed transition, one can detect each transition to a metastable state. These characteristics make it possible to study the spectrum of a single ion with great precision. The vibrational energy states of the bound ion are quantized. We have used laser-sideband-cooling to drive the ion to the lowest energy level of the harmonic well of the trap.

Experiment

A mercury atom that is ionized by a weak electron beam is captured in the harmonic well created by an rf potential applied between the electrodes of a miniature Paul trap (1,2). The ring electrode has an inner diameter of about 900 μm and is placed symmetrically between two endcap electrodes that are separated by about 650 μm. The frequency of the rf potential is about 21 MHz. Its amplitude can be varied up to 1.2 kV. The classical motion of the ion consists of a small-amplitude oscillation, at the frequency of the applied rf potential, superimposed on a larger-amplitude harmonic motion, called the secular motion. The frequencies of the secular motion depend on the strength of the rf field (and any static field applied to the electrodes) and were typically 1-4 MHz. The ion is laser cooled to a few millikelvins by a few microwatts of 194 nm cw laser radiation (3) that is frequency tuned below the $5d^{10}6s\ ^2S_{1/2}$ - $5d^{10}6p\ ^2P_{1/2}$ first resonance line (1,4). In order to cool all motional degrees of freedom to near the Doppler cooling limit ($T = \hbar\gamma/2k_B \simeq 1.7$ mK) the 194 nm radiation irradiates the ion from 2 orthogonal directions, both of which are at an angle of 55° with respect to the symmetry (z) axis of the trap. The 282 nm radiation that drives the narrow $5d^{10}6s\ ^2S_{1/2}$ - $5d^96s^2\ ^2D_{5/2}$ transition is obtained by frequency-doubling the radiation from a narrowband cw ring dye laser. In the long term, the laser is either stabilized by FM optical heterodyne spectroscopy to a saturated absorption hyperfine component in $^{129}I_2$ (5) or directly to a stable high finesse reference cavity (6). The frequency of the laser is scanned by an acousto-optic modulator that is driven by a computer controlled synthesizer. Up to a few microwatts of 282 nm radiation could be focussed onto the ion in a direction counterpropagating with one of the 194 nm light beams.

Optical-optical double resonance (electron shelving) (1,2,4,7-11) with a net quantum amplification in excess of 100 at 10 ms is used to detect transitions driven by the 282 nm laser to the metastable $^2D_{5/2}$ state. The fluorescence from the laser-cooled ion is constant when it is cycling between the $^2S_{1/2}$ and $^2P_{1/2}$ states and zero when it is in the metastable $^2D_{5/2}$ state (1,4,7,8). Thus the $^2S_{1/2}$ - $^2D_{5/2}$ resonance

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spectrum is obtained by first probing the S-D transition at a particular frequency near 282 nm, then turning off the 282 nm radiation, turning on the 194 nm radiation, and looking for 194 nm fluorescence. The two radiation fields are alternately applied to avoid light shifts and broadening of the narrow S-D transition. The absence of 194 nm fluorescence indicates that a transition into the metastable D state has occurred; its presence indicates that the ion has remained in the ground state. The 282 nm frequency is then stepped and the measurement cycle repeated. Each new result at a particular 282 nm frequency is averaged with the previous measurements at that frequency. The normalization of the signal is 1 for each measurement of high fluorescence and 0 for each measurement of no fluorescence. The high fluorescence level makes it possible to determine the state of the atom with almost no ambiguity in a few milliseconds. Thus, it is easy to reach the quantum noise limit of a single atomic absorber (1). Figure 1 shows the signal from an 8 MHz scan of the 282 nm laser through a Zeeman component of the S-D transition in $^{198}Hg^{+}$ (1). The Doppler-free central feature (carrier) and the motional sidebands due to the secular motion of the cold ion are fully resolved (12,13). The number and strength of the sidebands are a direct measure of the amplitude of the ion's motion and of its temperature.

In Fig. 2, we show a high resolution scan through the Doppler-free resonance of the $^{2}S_{\frac{1}{2}}(F = 0, m_F = 0) - {}^{2}D_{5/2}(F = 2, m_F = 0)$ transition in $^{199}Hg^{+}$ which is first-order field independent at a magnetic field $B \approx 0$. The full width at half maximum (FWHM) is approximately 86 Hz at 563 nm (172 Hz at 282 nm). This corresponds to a fractional resolution of better than 2×10^{-13} ($Q \approx 5\times10^{12}$). For this trace the laser was spectrally narrowed by locking to a mechanically, acoustically and thermally quiet reference cavity that had a finesse of about 60,000. The

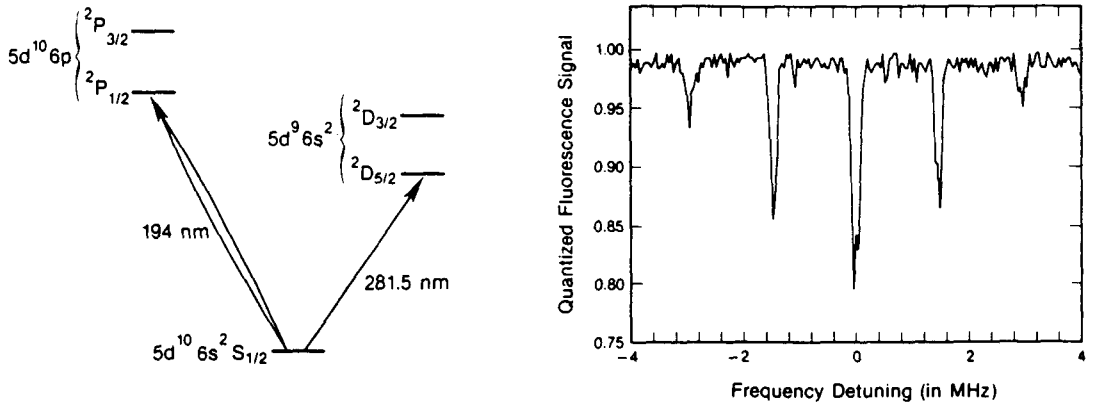

Fig. 1. On the left is a simplified energy-level diagram for $^{198}Hg^{+}$. The 282 nm transition can be observed by monitoring the 194 nm fluorescence. If the ion makes a transition from the $^{2}S_{\frac{1}{2}}$ to the $^{2}D_{5/2}$ level the 194 nm fluorescence disappears. For the figure on the right, the relative detuning from line center is plotted in frequency units at 282 nm. On the vertical axis is plotted the probability that the 194 nm fluorescence is on immediately after the 282 nm pulse. The Doppler-free recoilless-absorption-resonance or carrier (central feature) can provide a reference for an optical frequency standard. (From Ref. 1)

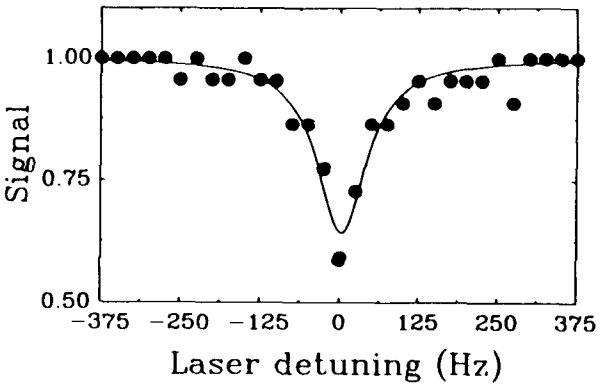

Fig. 2. High resolution scan through the Doppler-free resonance of the $^2S_{\frac{1}{2}}(F = 0, m_F = 0)$ - $^2D_{5/2}(F = 2, m_F = 0)$ transition in a single laser cooled $^{199}Hg^+$ ion. A frequency doubled and stabilized 563 nm laser ($\nu \approx 5\times10^{14}$ Hz) is stepped through the resonance in 25 Hz increments. The full width at half maximum is about 86 Hz. The integration time per point is about 0.5 s.

frequency of the laser fluctuates less than 50 mHz relative to this reference cavity. This is determined from the measurement of the noise in the error signal. The actual frequency fluctuations of the laser are governed by the stability of the mechanically and thermally isolated reference cavity (6). The natural linewidth of the S - D transition is approximately 1.7 Hz (2). The measured linewidth in Fig. 2 is likely limited by low frequency fluctuations in the length of the stable reference cavity (14). Better mechanical isolation of the reference cavity might permit us to reach the 1.7 Hz resolution limit.

The possibility of cooling the Hg^+ ion further, to the zero point energy of motion, is intriguing for several reasons. Cooling so that the average occupational number $\langle n_v \rangle$ for the motional energy of the bound atom is zero is a fundamental limit to laser-cooling for any bound particle (1,15) and forces a quantum mechanical treatment of the atom-trap system. Driving a single atom in a macroscopic trap to the zero point energy of motion exploits the benign environment near the center of an rf trap. Finally, if an ion is prepared in the lowest vibrational state, experiments such as squeezing the atom's position and momentum can be demonstrated (16).

In a rigorous treatment of the ion-trap system, stationary states do not exist since the trapping potential is time dependent. However, quasi-stationary states, obtained by solving for the eigenvalues of the Floquet operator, do exist (17,18). That these states correspond closely to the stationary states of the pseudo-potential of the rf trap is verified by the spectrum shown in Fig. 1. The carrier (at frequency ω_0) results from transitions in which the vibrational quasi-energy is unchanged. The upper and lower sidebands, spaced by multiples of the secular frequencies ($\omega_0 \pm n\omega_v$), correspond to transitions which increase or decrease the quasi-energy. Recently, we have cooled a single $^{198}Hg^+$ ion to the lowest vibrational state ($n_v = 0$) by a method called optical sideband cooling (15). First, the ion was laser-cooled to a few millikelvins by radiation scattered from the strong transition at 194 nm. This reduced the vibrational quantum number to a mean value of $\langle n_v \rangle \approx 12$. The secular frequency was about 3 MHz. Laser radiation tuned to the frequency of the first lower vibrational sideband (at frequency $\omega_0 - \omega_v$) of the narrow S-D transition was then applied to the ion. For each photon re-emitted at the unshifted carrier frequency, the vibrational energy was reduced by $\hbar\omega_v$. After the sideband cooling, laser radiation of saturating intensity was applied at the lower sideband frequency.

Absence of absorption indicated that the ion was in the $n_v = 0$ state. The ion was found to be in the $n_v = 0$ state about 95% of the time.

Starting from the ground vibrational state ($n_v = 0$), the absorption of a single quantum of energy at a frequency corresponding to the secular vibrational frequency (ω_v) would raise n_v by one unit. This could be detected with an efficiency of nearly 100%. Also, it should be possible to produce squeezed states (16) of the atom's motion from the zero point energy state by a sudden, non-adiabatic weakening (and, in general, shifting) of the trap potential or by driving the atomic motion parametrically at $2\,\omega_v$. If after some time the atom could then be returned to the $n_v = 0$ state by reversing the above procedures, the zero point energy state could be detected by the absence of the lower sideband.

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