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Ion-number-density-dependent effects on hyperfine transition of trapped $^{199}Hg^{+}$ ions in quadrupole linear ion traps

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ABSTRACT

The ion-number-density-dependent frequency offsets and broadening of the ground state hyperfine transition spectra of trapped $^{199}Hg^{+}$ ions were measured as a function of the end-cap voltage of the quadrupole linear ion trap. The number density of trapped $^{199}Hg^{+}$ ions in the quadrupole linear trap was controlled by the end-cap voltage. The fractional frequency stability of $^{199}Hg^{+}$ hyperfine transition to the 1 mV end-cap voltage variation was preliminary estimated to be less than 1×10^{-16}. The causes of the ion-number-density-dependent frequency shift and spectrum broadening were analyzed theoretically and explained.

1. Introduction

The discharge-lamp-pumped and buffer-gas-cooled mercury-ion microwave frequency standard in a linear trap has attracted much attention in recent years [1–5]. The main reason for this is that the trapped ions are almost immune to environmental perturbations, and the linear-trap mercury-ion microwave frequency standard has potentially high stability [6,7]. Its long-term stability in the Jet Propulsion Laboratory (JPL) has been measured at $< 2 \times 10^{-16}$, which can be further improved by measuring and monitoring of the known frequency biases [8]. The three main systematic issues affecting the long-term stability of these standards are variation in the number of the trapped ions, ambient magnetic field, and background pressure [9]. These effects correspond to three main frequency shifts respectively, i.e., the second-order Doppler frequency shift (ion number and temperature) [10], the Zeeman frequency shift [11], and the buffer gas frequency shift [12]. These residual systematic effects will also result in broadening of the transition spectrum, such as Doppler broadening [13] and buffer-gas pressure broadening [12], which reduce the performance of the microwave frequency standards of the trapped $^{199}Hg^{+}$ ions. In order to increase the signal-to-noise ratio in the measured stored ions hyperfine resonance used in frequency standards, it is desirable to have as many trapped ions as possible. However, changes in the number or number density of trapped ions also weakens the stability and accuracy of trapped ions frequency standards [7,14]. Therefore, accurate measurement and control of ion-number-density-dependent effects on the trapped $^{199}Hg^{+}$ ions is necessary for the performance improvement of these standards.

In this paper, the ion number density of stored $^{199}Hg^{+}$ ions in the quadrupole linear trap was first adjusted via the end-cap voltage. Subsequently, the center frequency offset and broadening of the hyperfine transition spectrum of the $^{199}Hg^{+}$ ions as a function of the end-cap voltage of the quadrupole linear ion trap were measured experimentally. The fractional frequency stability of the $^{199}Hg^{+}$ ions clock transition to the typical end-cap voltage variation was estimated. Finally, theoretical analysis of the ion number-density-dependent frequency shift and spectrum broadening was performed by considering the axial ion number density varying with the end-cap voltage. This work provides the basis for the control and reduction of ion number density effects on $^{199}Hg^{+}$ ions microwave frequency standards in quadrupole linear traps.

2. Experimental setup

The experimental apparatus of the quadrupole linear-trap mercury-ion microwave frequency standard is shown in Fig. 1(a). It

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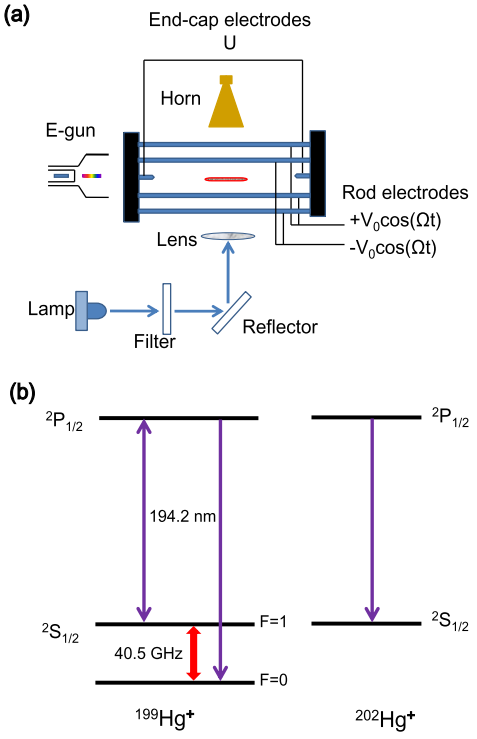

Fig. 1. (Color online.) (a) The experimental setup of the trapped $^{199}Hg^{+}$ ions microwave frequency standard in a quadrupole linear trap. U is the DC voltage amplitude of the end-cap electrodes. V_0 is the RF voltage amplitude of the rod electrodes, and Ω is the angular frequency of the RF field. (b) Energy levels of $^{199}Hg^{+}$ and $^{202}Hg^{+}$ ions, including the microwave resonance transition at 40.5 GHz and the optical interrogation transition at 194.2 nm.

consisted of four parallel rod electrodes, evenly fixed on a ceramic ring with a radius of 10 mm. The radio frequency (RF) voltage for radial confinement of ions was applied to the rod electrodes. Direct current (DC) voltage was applied to the end-cap electrodes, providing an axial confinement potential to prevent the escape of ions along the axis. The quadrupole linear trap was placed in an ultrahigh vacuum chamber with a pressure of approximately 1×10^{-10} Torr. Neutral ^{199}Hg atomic vapor was generated by heating HgO powder in an oven, which was connected to the vacuum chamber. The electron beam from the heated LaB_6 cathode of e-gun bombarded neutral ^{199}Hg atoms, creating the $^{199}Hg^{+}$ ions. Helium buffer gas with a pressure of approximately 1×10^{-5} Torr was introduced into the vacuum chamber through a quartz leak to cool the ions to room temperature.

A $^{202}Hg^{+}$ discharge lamp was used as the state preparation/interrogation light source, owing to the natural coincidence between the transition of the $^{202}Hg^{+}$ isotope from $^2S_{1/2}$ to $^2P_{1/2}$ (wavelength $\lambda = 194.2$ nm) and the transition of the $^{199}Hg^{+}$ isotope from $^2S_{1/2}$ (F = 1) to $^2P_{1/2}$. This 194.2 nm ultraviolet (UV) light was focused onto the center of the trap by an excitation light path. The $^{199}Hg^{+}$ ions were excited from the upper ground hyperfine state $^2S_{1/2}$ (F = 1) to the excited state $^2P_{1/2}$ by 194.2 nm light, and returned back to both hyperfine states $^2S_{1/2}$ (F = 1) and $^2S_{1/2}$ (F = 0) through spontaneous emission. Continued illumination with the UV light led to the ions populating the lower ground hyperfine state, $^2S_{1/2}$ (F = 0). Microwave radiation near 40.5 GHz was fed into the trap by a horn antenna to induce the ground state hyperfine transition of trapped $^{199}Hg^{+}$ ions from $^2S_{1/2}$ (F = 0, $m_F = 0$) to $^2S_{1/2}$ (F = 1, $m_F = 0$), as shown in Fig. 1(b). The fluorescence from the spontaneous emission of trapped $^{199}Hg^{+}$ ions, which is an indicator of the number of ions that underwent the hyperfine transition from F = 0 to F = 1, was collected by the photon counter via the detection light path (perpendicular to the paper).

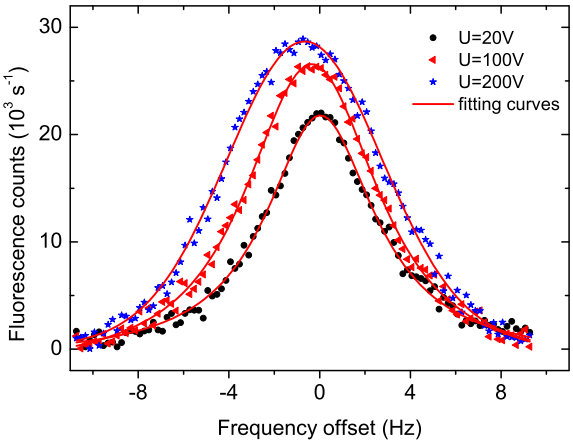

Fig. 2. (Color online.) The hyperfine transition spectra of trapped $^{199}Hg^{+}$ ions under end-cap voltages of 20, 100, and 200 V. The solid lines are the Voigt fits to the experimental data.

In contrast to our previous studies [15–18], the excitation and detection light path were changed from the straight to reflection type in the present experimental setup. A pair of dielectric reflective filters with > 90% reflectance for 194.2 nm ion fluorescence were used for both focusing the source light from a $^{202}Hg^{+}$ lamp onto the trapped ions and for collecting fluorescence from the ions. This improvement saved on space and facilitated the miniaturization of the physical package of the mercury-ion microwave frequency standard.

3. Experimental results

Since the $^{199}Hg^{+}$ ions trapped at the center of the ion trap distribute into a "cloud" [10,19], it is difficult to accurately measure their number density. As mentioned above, ions are confined in the trap mainly by the radial RF potential (provided by the RF field, $\pm V_0\cos(\Omega t)$) and axial DC constraint (provided by U). Therefore, the trapped ion number density can be varied by changing any one of these trapping parameters. The complex interaction between the radial RF confinement potential and V_0 or Ω [19–21] means that a small change in these parameters may result in ions going beyond the stable solution area of the Mathieu equation, which describes the ion motion, leading to very few confined ions in the trap [6,21]. Therefore, the trapped ion number density is usually controlled by adjusting U of the linear trap over a certain range since there is a linear relationship between DC confinement potential and U [14,22,23].

In order to observe the ion number density effects on mercury-ion microwave frequency standards, the spectra of the ground state hyperfine transition of trapped $^{199}Hg^{+}$ ions under various end-cap voltages were obtained with the microwave-optical double-resonance method. Fig. 2 presents the hyperfine transition spectra scanned with end-cap voltages of 20, 100, and 200 V. The scanning range of the microwave frequency was ±10 Hz near the 40.5 GHz and the power of the microwave radiation output from the microwave source was −30 dBm. The microwave source was referenced to a hydrogen maser. The ions were loaded before every measurement circle and the e-gun was off during the measurements to ensure no new ions were created. Ions can be stably confined for more than 1000 s which was enough to finish a single measurement. The experimental data were fitted by a Voigt function, the convolution of Lorentzian and Gaussian functions, since the broadening of the measured transition spectra was induced by more than one factor. The deviation of the scattered data from the fitting curve was derived from the background stray light noise. On comparing these three typical transition lines, the signal intensities