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# Fluorescence Detection and Buffer Gas Cooling of Trapped Mercury Ions in Paul Trap *

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*Hg ions are confined in a hyperboloid ion trap. With the rf discharge $^{202}$Hg isotope lamp, the fluorescence signal of trapped Hg ions is observed. By means of buffer gas cooling, the ionic temperature is reduced. As a result, the trapping time is increased and the signal-to-noise ratio (SNR) of the fluorescent signal is improved. The temperature of ion cloud is estimated by measuring the space charge shift.*

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Ion traps have come to be increasingly versatile and important tools in atomic and molecular physics. In the trapping region the perturbations become very small. Thus relatively long interaction times[1] between ionic systems and external radiation fields can be realized. When excited by microwave, the trapped ions can easily fulfil the Dicke criterion,[2] which makes the first-order Doppler effect negligible. Due to those inherent advantages, the ion trapping techniques are widely used in frequency standard. $^{199}Hg^+$ is one of the preferred candidates for microwave frequency standards because of the comparatively simple ground-state energy-level schemes and the large hyperfine splitting frequency 40.5 GHz.[3] There have been several experiments carried out on the $^{199}Hg^+$ microwave frequency standard.[4−7] Among them, JPL's $^{199}Hg^+$ frequency standard based on the linear ion trap has reached the long term stability $1 \times 10^{-16}$,[8,9] which is the best stability of microwave frequency standard to date. In this experiment, the use of $^{202}$Hg isotope discharge lamp as light source replaces the laser systems, which makes the clock attractive for space applications. Another crucial aspect of the $Hg^+$ clock technology is the use of buffer gas to cool the ions and to reduce the second-order Doppler shift.[10,11] In this Letter, we illuminate our experimental results about the fluorescence detection and buffer gas cooling of trapped mercury ions.

In our work, the ion trap is typically a hyperboloid Paul trap composed by two end caps and a ring electrode. The trap radius $r_0$ is 20 mm, half the distance between the endcaps $z_0$ is 14.14 mm, the frequency of the confining field $\Omega$ is $2\pi \times 500$ kHz, $U_0$ is the voltage of dc field and $V_0$ is the amplitude of ac field. The ion trap in the experiment is made of copper. Four holes are drilled into the ring as entrance and exit of light and electron beam. A piece of mesh is used to cover the fluorescence outlet hole on the top end cap to compensate for the geometrical defect caused by that hole. The trap is put inside a vacuum chamber at a background pressure of about $3 \times 10^{-10}$ torr. A suitable pressure vapour of neutral mercury can be obtained by controlling the temperature of the mercury oxide (HgO).

A discharge lamp rather than laser plays the role of the pumping source in our work. The lamp is filled with $^{202}$Hg isotope and inert buffer gas and made of fused quartz with a 2 cm long 3 cm diameter cylindrical stem for an easy control of the Hg vapour pressure. The lamp is excited with 40 W of rf power (150 MHz). In ultraviolet spectrum region, mostly, the lamp provides both the atomic line at 2537 Å and the ionic line at 1942 Å.[12] Interrogated by the 1942 Å light from the lamp, the confined Hg ions are excited and then the fluorescence of the same wavelength can be detected. However, the intensity of 2537 Å line is usually about 1500 times greater than the intensity of the desired ionic line 1942 Å. To further reduce the intensity of the 2537 Å and to suppress the background light noises, an atom filter filled with $^{202}$Hg is smartly connected in front of the bulb. In our experiment we adjust the stem temperature at about 40°C to make sure the lamp working at a best point that results in about same transmitted intensities at 2537 Å and

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1942 Å.

The systems of fluorescent detection are shown in Fig. 1. It is difficult to detect fluorescent signal directly from the trapped ions because of the low sensitivity caused by the weak intensity of 1942 Å light, the great stray-light background and the low ion cloud density. In our experiment, the desired pumping lights of 1942 Å are focused into the centre of the trap with a set of optical lens. The radius of the light beam is about 1.5 mm at the centre of the trap. A photomultiplier tube (electron tubes $9402B$) is used to detect the fluorescence of ions through an interference filter and an optical lens. The photomultiplier tube is sensitive at the wavelength from 110 nm to 360 nm with the peak quantum efficiency 10% at 200 nm and the interference filter's bandwidth is about 20 nm with the peak transmission 10% at 200 nm. All the optical windows and lens are made of JGS1 synthesized quartz with the transmission 80% at 1942 Å. The total collecting solid angle is about 2% out of $4\pi$.

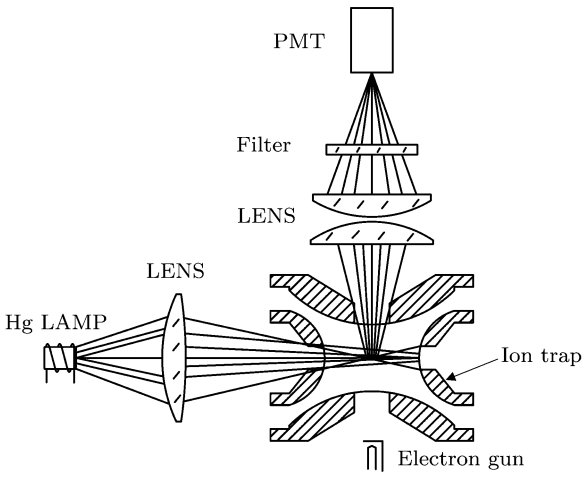


**Fig. 1.** The schematic of our experimental setup.

In our experiment, by heating the HgO powder to about 178°C, the partial pressure of the mercury is about $1.2 \times 10^{-9}$ torr. Electrons emitted from the hot filament are injected into the centre of the trap to ionize the neutral mercury atom. In order to trap maximum number of ions, the dc and ac components of the confining voltages are set to 1046 V and 26 V, respectively.

Excited by the discharge mercury lamp, the fluorescence signal can be observed as soon as we turn on the electron gun. Then the fluorescence signal disappears quickly after the rf drive field is turned off (see Fig. 2). The vanishing of the signal is obvious because there is no confining field to the trapped ions. In the other way, due to the finite lifetime of trapped ions, the signal decreases within a few seconds after cutting off the electron beam (see Fig. 3). We can estimate the trapping time to be about 16 s according to the fitted exponential decay curve.

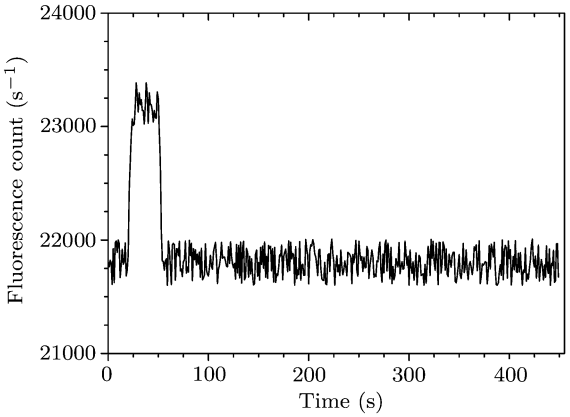


**Fig. 2.** The change of fluorescence signal versus time, where the electron gun is turned on at $t = 20$ s and then the rf field is cut off at $t = 50$ s.

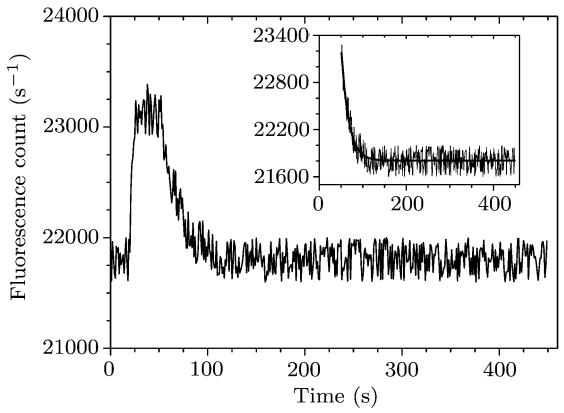


**Fig. 3.** Fluorescence signal versus time, where the electron gun is turned on at $t = 20$ s and then turned off at $t = 50$ s. The inset shows the exponential decay of the fluorescent signal after the electron gun is turned off.

Generally, a single ion can be confined in the ion trap stably for infinite time under ideal condition. However, in our case the production of $Hg^+$ requires a certain extent of neutral Hg background gas. Thus the collisions with background gas will increase kinetic energy of the ions and then reduce the lifetime of trapping. The charge-exchange between the trapped ions and neutral gas can decrease the trapping time as well. Moreover the geometrical defects caused by the finite size and holes for light and electrons are also disadvantages for trapping more or less.

In order to increase the trapping lifetime of the ions, we have to cool the ions. It has been demonstrated[11,13–15] that the light buffer gas is a very efficient medium to reduce the energy of atoms or ions. Compared with other methods of cooling, buffer gas cooling relies only on the elastic collisions of the species to be trapped with a cryogenically cooled gas.

Thus it is independent of any particular energy level pattern and it is a general cooling technique applicable to any atomic or ionic species.

In our experiment, the buffer gas Helium is taken into the vacuum chamber through a quartz leak consisting of a thin quartz tube wrapped with tungsten wire. With the quartz leak heated, the helium can enter the chamber through quartz tube because of diffusion. Different helium pressure can be obtained by changing the temperature of the quartz leak.

Figure 4 shows the fluorescence signal at the helium pressure about $5 \times 10^{-6}$ torr. The fitted exponential decay curve indicates the trapping time to be about 180 s. Obviously, the confined time is prolonged in comparison with the case that there is no helium introduced into vacuum system.

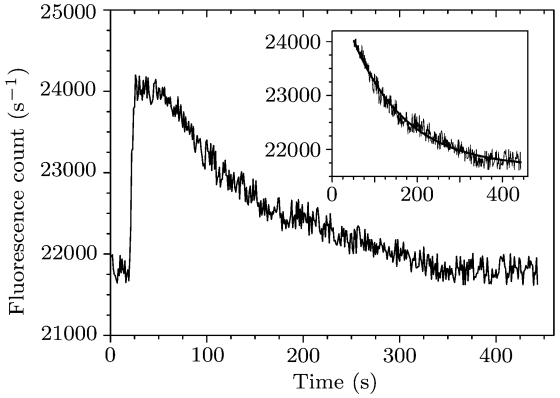


**Fig. 4.** Fluorescence signal versus time, where the electron gun is turned on at $t = 20$ s and then turned off at $t = 50$ s. The inset shows the exponential decay of the fluorescent signal after the electron gun is turned off.

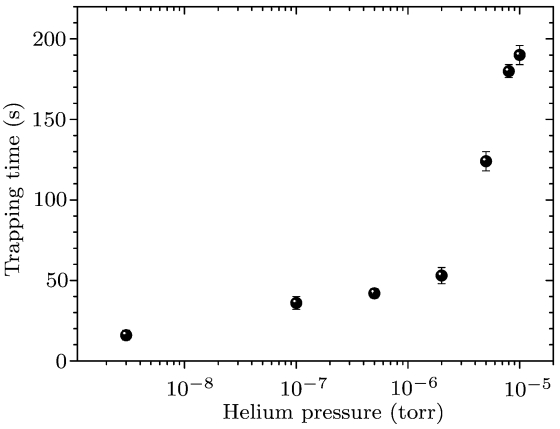


**Fig. 5.** Trapping time increases as the rise of Helium pressure.

Adjusting the temperature of the quartz leak, we can reach several different helium pressures. At these helium pressures, we measure the confined time of the ions. The results are shown in Fig. 5, from which we can find that the trapping time of $Hg^+$ increases with the rising helium pressure.

At the same time, we find that with the rising buffer gas pressure, the ion fluorescent signals increase, as shown in Fig. 6. This means that in the case of higher buffer gas pressure, the ion number density increases.[10,15] Thus by means of buffer gas cooling, the SNR of fluorescent signal can also be improved.

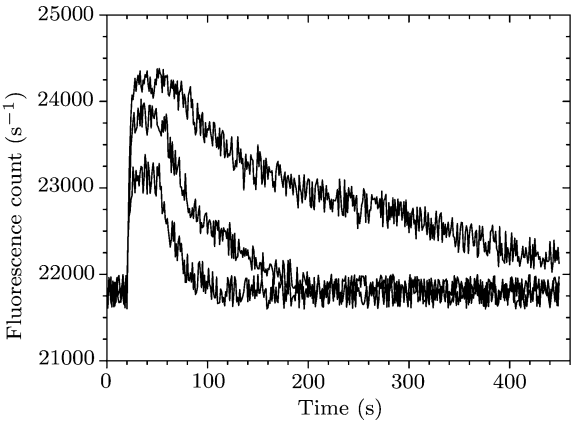


**Fig. 6.** Fluorescence signals in difference helium pressure. The signals from top to bottom correspond to helium pressures $1 \times 10^{-5}$ torr, $2.1 \times 10^{-6}$ torr, $< 1 \times 10^{-10}$ torr. The electron gun is turned on at $t = 20$ s and then turned off at $t = 50$ s

Generally, the temperature of the confined ion is measured by scanning ionic Doppler spectrum.[16] In our work, however, an easy way which founds on spacial charge effect is adopted to estimate the ionic temperature. The principle and experiment are described in the following.

Ions confined in the trap would undergo a simple harmonic motion in effective potential at a characteristic macro motion frequency

$$\omega_z = \sqrt{\frac{8e^2V_0^2}{m^2\Omega^2(r_0^2+2z_0^2)} - \frac{4eU_0}{m(r_0^2+2z_0^2)}}, \qquad (1)$$

along the $z$ axis,[17] where $e$ and $m$ are the ion charge and mass respectively. According to the ion-excitation method,[18,19] the ion resonance signal can be obtained when the macro motion frequency $\omega_z$ equals to the frequency of the additional detection field. The ion-excitation experimental circuit used in our experiment is shown in Fig. 7. At high temperatures, the ion cloud is dilute and the ions see a negligible spacial charge effect. At lower temperatures, the density of the ions increases and the coulomb interaction between ions becomes stronger.[10] In this case, the effective potential is modified by the ionic space-charge, which results in a shift of macro motion frequency.[20] This macro motion frequency shift can be compensated by adjusting dc bias $U_0$ according to Eq. (1). The additional dc

bias is given by[20]

$$\Delta U = \frac{ez_0^2}{4\pi\varepsilon_0\rho_0^3}N, \quad (2)$$

where $z_0$ is half of the distance between the endcaps, $\rho_0$ is the radius of the ion cloud. The total ion number $N$, which is proportional to the ion's resonance signal, can also be decided by the ion-excitation method. Assuming that distributing of the ion's spacial charge is uniformly spread over the trapping region, the mean kinetic energy or the temperature of ions can be estimated by[21]

$$\overline{E} = \frac{1}{2}m\overline{\langle v^2\rangle} = \frac{1}{2}m\Big(\omega^2 + \frac{1}{8}\Omega^2 q^2\Big)\overline{\langle \rho_0^2\rangle} = \frac{1}{2}kT, \quad (3)$$

where $q = 2eV_0/(mr_0^2\Omega^2)$ is the trapping parameter.

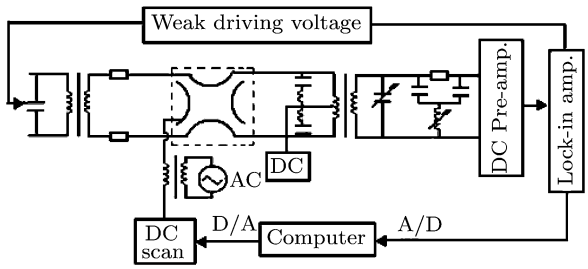


**Fig. 7.** A sketch for ion-excitation method. A weak rf excitation field at frequency $\omega$ is applied to the cap electrodes of the trap. Sweeping the dc bias over an appropriate range, a resonant excitation signal can be observed when $\omega$ is equal to $\omega_z$.

At different helium pressure, $\Delta U$ can be measured and the total ion number can be calculated by ion-excitation method. Using Eqs. (2) and (3) we can obtain the ion's temperatures at different helium pressures. The result is shown in Fig. 8.

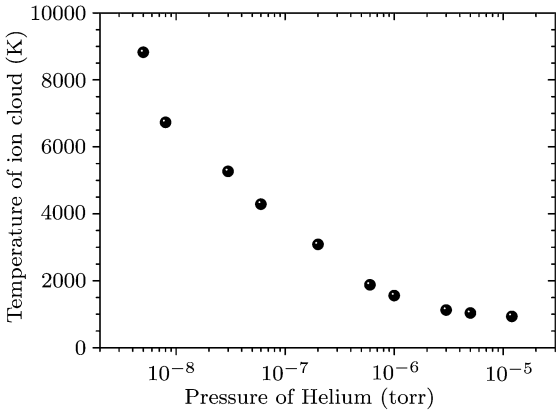


**Fig. 8.** Ion temperature vs the pressure of helium.

As shown in Fig. 8, at the pressure of $1.2 \times 10^{-5}$ torr, the ion cloud gets the lowest temperature about 1000 K and the maximum trapped ion number about $10^5$. In order to reduce the temperature and to increase the confined ion number, it is necessary to improve our vacuum system to make sure it can working in a higher pressure of buffer gas.

In conclusion, we have observed the trapped Hg ion fluorescence signal by using rf discharge $^{202}$Hg isotope lamp as excited light source. Helium has been successfully introduced in our system for cooling the confined ions. By means of buffer gas cooling, we have reduced the ionic temperature, increased the trapping time and improved SNR of the fluorescent signal. The temperature of ion cloud has been estimated by measuring space charge shift at different helium pressure. Those are important steps for us towards the trapped $Hg^+$ microwave frequency standard.

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