

Demonstration of long vacuum integrity lifetime of trapped ion standard package

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Abstract—A compact Hg ion trap package that was vacuum-sealed since 9 years has been demonstrated to be successfully operational showing excellent ion-trap lifetime exceeding 400 days. In addition to the vacuum package, the same 9-year-old optical and detection packages are utilized to obtain these results. Charge transfer relaxation effects between neutral Hg and trapped Hg ion are studied. This work shows the reliability of such units in view of next-generation ground and space-borne trapped ion clocks.

I. INTRODUCTION

Precise navigation has become an indispensable part of our day-to-day lives. Space navigation and deep-space tracking can be enhanced by precise onboard clocks. A promising avenue for future precision space clocks is the trapped Hg⁺ standard [1] [2]. An Hg⁺ standard has advantages over other compact standards. For instance, it does not require lasers; therefore there is no complexity associated with operating and stabilizing lasers. The Hg ions in the trap are optically pumped by spectral lamp as used in compact rubidium clocks. Further benefits of Hg⁺ clock are that it requires no shutters, has low magnetic field sensitivity and no wall collisions (as in a Rubidium vapor cell clocks) [3] [4]. It is made of a completely sealed vacuum tube with no active pump, no consumables (as in cesium tube standards and hydrogen masers), no cryogenics, and no microwave cavities. The absence of wall-collisions offers a high atomic line-Q.

In this paper, we present a compact Hg ion quadrupole linear trap package (volume of 1 liter) that was vacuum-sealed since 2005 (about 9.5 years) in our laboratory. We report the long shelf life of titanium vacuum tube and the improvement of the vacuum in a sealed system only by a passive getter pump. Furthermore, longer trap lifetimes of trapped ions in a quadrupole linear trap exceeding one year will be demonstrated, along with investigations on Hg-Hg⁺ charge transfer phenomena.

II. BRIEF HISTORY OF THE PACKAGE

The quadrupole linear trap package used in the studies presented here was fabricated in May 2003. Below a brief history of the usage and evolution of this package relevant to this work is presented as follows:

- May 2003 : Quadrupole assembly was fabricated.
- July 2005 : Quadrupole inserted into the trap/clock system.

- Aug 2005 : First microwave clock signal observed.
- October 2005: Getter pump valve closed. The system was sealed since then; ~ 9 years.
- March 2007 : Aluminum Bell jar tests to simulate the space environment [5].
- May 2011: The system (trap and vacuum) last used, since then the system has been idle.

The optical- and detection-packages that were used in 2005 have been retained in the package. The experiments on this sealed package have been conducted since 2005 till 2011. The trapped ion lifetime tests have been conducted using this package, and were already reported in 2009 [5]. In 2009, the lifetime up to six month was reported using this package. Since 2011, this vacuum tube package, the optical package and the detection package have been in idle state, and they were operated again during November 2014 and the tests are reported in the following sections.

III. EXPERIMENTAL SETUP

The physics package that includes – quadrupole linear trap, optics components along with ²⁰²Hg discharge lamp and the photomultiplier detector are shown in Fig. 1. This package was designed and fabricated in 2003 and the details were already published [6]. The main focus of this package design is to eliminate the use of active mechanical pumping and only use the passive method of getter pumping to maintain low vacuum pressure. On the other hand, these getter pumps will not pump the noble buffer gases, thereby eliminating the need of continuous supply of buffer gas that is necessary for cooling the trapped ions. The essence of usage of such getters rely on better cleaning and high temperature (~ 400 °C) baking. The trap rods are made of molybdenum (non-magnetic) in order to get narrow clock transition (40 GHz) linewidths. The optical and detector packages are orthogonal to each other. The light source from a ²⁰²Hg lamp is used for optical pumping of the trapped ions and the emitted ion fluorescence is collected using the Photomultiplier (PMT) detector assembly. Each assembly has focusing lenses and dichroic mirrors ($> 95\%$ reflectance for 194 nm fluorescence signal from the ions and $< 10\%$ reflectance for the parasitic 254 nm light from a background neutral Hg transition). This helps in increasing the signal-to-noise (S/N) ratio. Further details of the optical and the detection packages are explained in [6]. This package has a quadrupole linear trap part and a multipole (16 pole) region

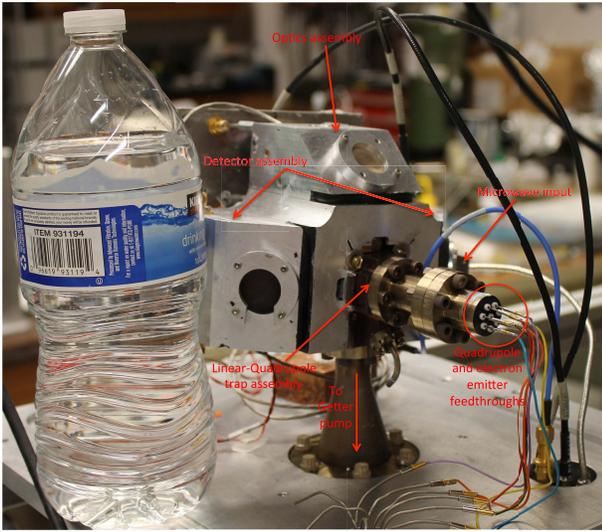


Fig. 1. One liter package showing the quadrupole linear trap feedthroughs and the electron emitter feedthroughs along with the optical and detection assemblies. One liter water bottle is placed to give a size perspective.

[6]. Neon buffer gas of 1×10^{-5} Torr is filled in to the vacuum package for cooling of trapped ions [7]. However, for our measurements presented in this work, we only use the quadrupole linear trap region, as we do not perform the clock stability measurements.

IV. EXPERIMENTS AND RESULTS

The system that was idle since May 2011 was turned on in the following steps. At first, the electron emitter was turned on and an emission current of $2.5 \mu\text{A}$ was measured, comparable to the previous values. This gave us an indication that the vacuum inside the package was intact. Following to this, the ^{202}Hg discharge lamp was turned on and the neutral Hg fluorescence at 254 nm was measured by heating the getter to about 40°C . The getter heating was required as there was adsorption of neutral Hg on the Getter medium. Once the neutral Hg fluorescence was seen, the rf voltage (295 Vrms at 1.83 MHz on single electrode) was applied to the quadrupole trap rods and ion trapping signal was observed.

A. Lamp optical pumping test

Optical pumping time of the Hg ions from a hyperfine ground-state via an excited state gives an indication and measure of 194 nm light intensity from the ^{202}Hg lamp [8] (also see ^{199}Hg and ^{202}Hg energy level diagrams for 194 nm interrogation in [8]). In our experiment, the pumping light was kept constant, but the microwave tuned to the resonance transition (~ 40.5 GHz) was switched on and off (cf. Fig. 2). When the microwaves are interrogated (switched on), the ions are pumped from the lower ground state ($|^2S_{1/2}, F=0\rangle$) to the higher ground state ($|^2S_{1/2}, F=1\rangle$), giving rise to the microwave signal as seen in Fig. 2. When the microwaves are turned off, the 194 nm light from the lamp optically pumps the ions again to the lower ground state, via the excited state $^2P_{1/2}$. An optical pumping time of $4.7(2)$ s was measured (cf. Fig. 2).

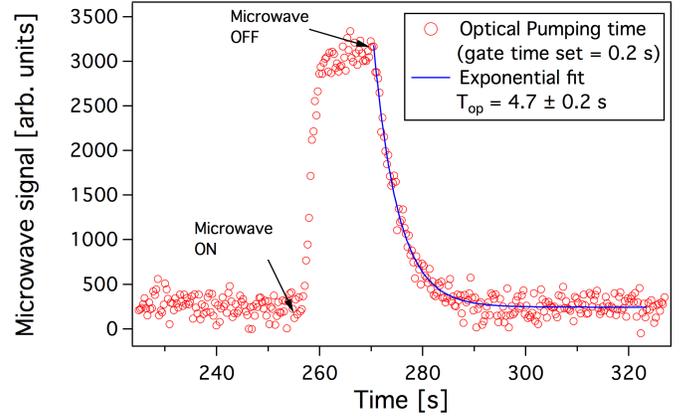


Fig. 2. Optical pumping time measured by the method of switching the microwave interrogation. Measurement gate time of 0.2 s was used for better resolution. An optical pumping time of $4.7(2)$ s was measured.

B. Rabi spectroscopy

Once the ions are loaded to the trap, they are optically pumped to the lower ground state by an optical pulse, and microwave interrogation is performed in the dark (i.e., when the pumping light is off) by detuning the microwave frequency, and finally, the pumped atoms to the upper ground state are detected by a short (or weaker) optical pulse, this is known as Rabi interrogation method. Typically, in our measurements the optical pumping pulse time of 5 s, microwave pulse of 4 s with a power of -26 dBm were used and the obtained typical Rabi curves are shown in Fig. 4 and Fig. 5. Sub-Hz linewidths are obtained giving a line-Q of $\sim 10^{11}$ with excellent S/N ratio. The line-Q and S/N for these resonances indicate excellent short-term stabilities of $\sim 1.5 \times 10^{-13} \tau^{-1/2}$. During these measurements, no magnetic shields were used to minimize the ambient magnetic fields and therefore clock transition was shifted from the unperturbed transition (40.507347996 GHz) by a few tens of Hz [7].

C. Ion cloud life-time

The prime objective of this package design was to eliminate the need for active mechanical pumps. Therefore, as pointed out earlier, the physics package (metal tube, UV windows, ceramics etc.) had to withstand the high temperature bakeout, to be operated in a sealed state using only a getter pump. The use of getter pumps also helps in size reduction. The measurement of the trapped ions' lifetime was done by recording the amplitude of the clock signal after ion loading has been done. Such a measurement using this package was already been demonstrated in [5]. Previously reported lifetime was 5000 hrs and with the same package, we have obtained the lifetimes of about 9888 hrs (412 days). The previous results along with newly measured lifetime data are shown in Fig. 3. It is to be noted that these measurements are done with out any replenishment of the ions. This indicates us of the improvement of the vacuum inside the tube by getter pumping for five more years. This not only gives an indication of the long vacuum integrity of our vacuum package, but also its longer shelf life making them excellent candidates for portable applications.

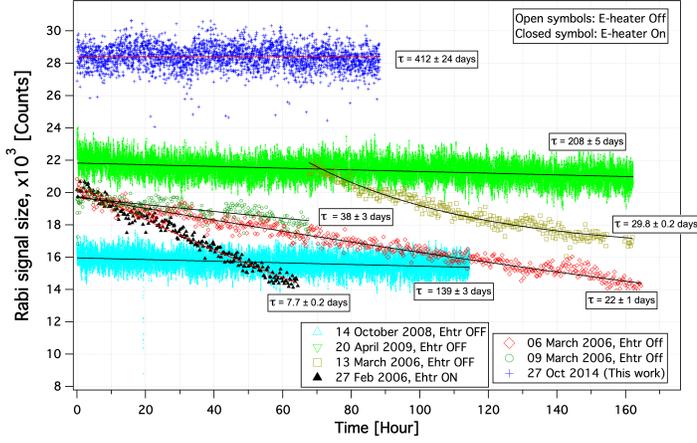
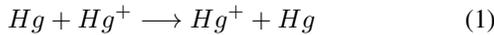


Fig. 3. Trap lifetimes measured with the same vacuum trap package at different times. Shows improvement in the ion trap lifetime after seal-off of the vacuum trap tube since 2004. The four longest trap times are 1000, 3000, 5000 and 9888 hours (to 1/e of initial ion signal). Except the longest lifetime of 9888 hrs, all the other data reported here were already published in [5]. The four long trapping times were measured over a 8 year period.

D. Charge transfer relaxation observations

The long ion trap lifetime presents an opportunity to study interesting phenomena that cause the relaxation of ions in the trap. We investigate the effect of charge transfer relaxations induced by the neutral Hg atoms on the trapped Hg ions. Fig. 4 shows a typical Rabi curve measured at a low background neutral Hg and contrarily, Fig. 5 shows the Rabi curve measured at a high background of neutral Hg. The background neutral fluorescence values obtained for these curves are 220k and 505k, respectively. An increase in neutral background of a factor of 2 reduces the signal size approximately by same amount, giving a direct measure of the effect of neutral Hg on signal size. This reduction in signal size is due to the charge transfer interactions that occur between the trapped ions and the background neutral Hg atoms [9] [10].



when a collision occurs, the Hg^+ ion in the trap is instantly lost.

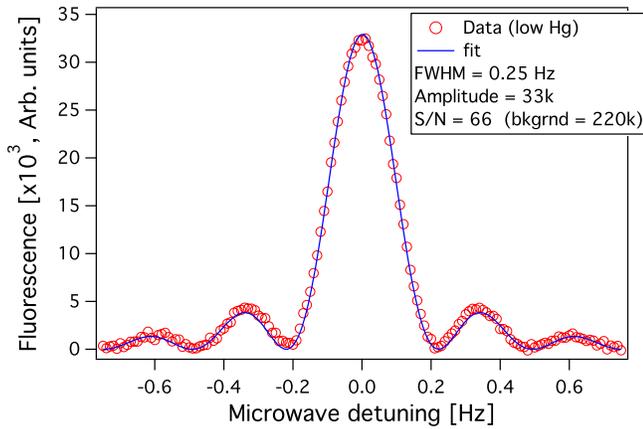


Fig. 4. Rabi curve obtained in the condition of lower background neutral Hg.

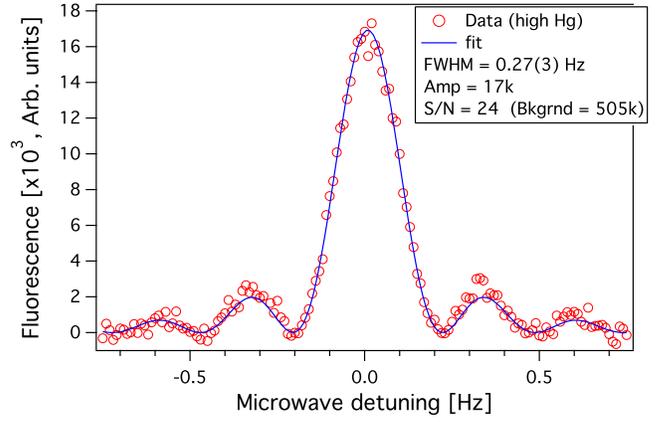


Fig. 5. Rabi curve obtained in the condition of a high background neutral Hg.

The temperature dependent resonant charge exchange collision cross-section, $\sigma_{res}(\epsilon)$, between neutral Hg and an Hg ion can be estimated from the equation [11]:

$$\sigma_{res}(\epsilon) = \sigma_{res}(\epsilon_1) [1 + a \ln(\frac{\epsilon_1}{\epsilon})]^2 \quad (2)$$

where, $\sigma_{res}(\epsilon_1)$, a and ϵ_1 are the positive approximation constants and the values for Hg-Hg⁺ collision are $164 \times 10^{-16} \text{ cm}^2$, 0.052 and 1 eV, respectively [11]. ϵ is the kinetic energy depending on the vapor temperature in eV. For our case, at a temperature of 343 K the mean relative velocity of atoms is 191 m/s and the energy equivalent to thermal velocity is 0.037 eV. Using the above values in Eqn. 2, we get the resonant collision cross-section to be $2.25 \times 10^{-14} \text{ cm}^2$.

In our setup there is no option to directly measure the neutral Hg density. However, one can estimate for the collision rate, Γ_{coll} , between Hg-Hg⁺ as a function of neutral Hg pressure by using the equation [12]:

$$\Gamma_{coll} = L_0 \cdot \bar{v} \cdot \sigma_{res}(\epsilon) \cdot \frac{P_{Hg}}{P_{Atm}} \quad (3)$$

where L_0 ($= 2.686 7774(4) \times 10^{25} \text{ m}^{-3}$ at 0°C and 1 atm.) is the Loschmidt's constant, $\bar{v} = \sqrt{8 \cdot k_B \cdot T / \pi \cdot \mu}$ is the mean relative velocity between Hg and Hg⁺, P_{Atm} is the atmospheric pressure (760 Torr) and P_{Hg} is the Hg pressure in Torr. k_B is the Boltzmann constant, T is the temperature of Hg vapor and μ is the reduced mass of the collision species (Hg in our case $= 3.3 \times 10^{-25} \text{ kg}$). For instance, if we consider an Hg pressure change of $1 \times 10^{-9} \text{ Torr}$ to $2 \times 10^{-9} \text{ Torr}$, the collision rate between neutral Hg and Hg-ion changes from 16 s^{-1} to 32 s^{-1} , by a factor of two as shown in Fig. 6

The above analysis shows that the effect is very sensitive to the Hg neutral density. In addition to the signal size, the linewidth also increases due to charge transfer collision interactions. Therefore, the consequence of the reduction in the resonant line-Q and S/N affects the clock's short-term stability. With these measurements, it is evident that lower vapor pressure of Hg is better for the clock operation. Consideration of the charge transfer relaxation phenomenon is of great value for improving the Hg⁺ clock performance as well as for fundamental physics process investigations.

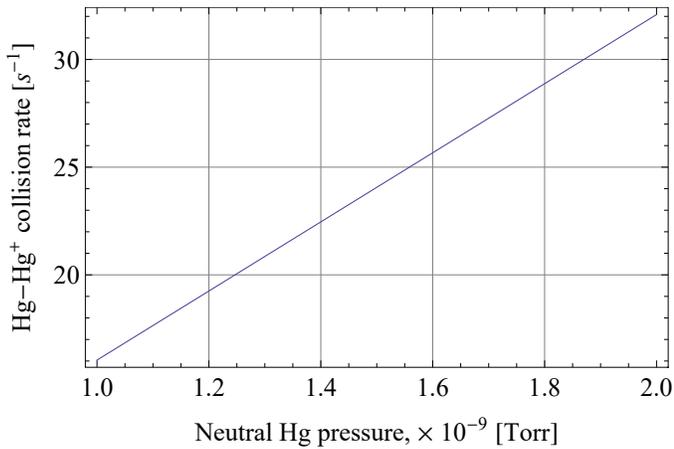


Fig. 6. Plot of collision rate between neutral Hg and Hg ion as a function of neutral Hg pressure.

V. CONCLUSION

The long vacuum integrity and long shelf life of a Hg ion trap system was presented. The optical pumping time with an old ^{202}Hg lamp and the Rabi signals with S/N of 66 indicating the potential for a short-term clock stabilities to 1×10^{-13} level were shown. The excellent trap lifetimes of more than 400 days (9888 hrs) with only getter pumped trap package was demonstrated. Furthermore, the unique environment of extremely long trap lifetimes was utilize to study the charge transfer relaxation between the trapped Hg ions and the background neutral Hg atoms. These studies are important in view of future portable Hg standards.

ACKNOWLEDGMENT

This work was carried out at the Jet Propulsion Laboratory (JPL), California Institute of Technology (Caltech), under contract with the National Aeronautics and Space Administration (NASA). Thejesh Bandi thank Swiss National Science Foundation (SNSF) for the fellowship through Early Postdoc Mobility (EPM) grant.

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