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A CRYOGENIC LINEAR ION TRAP FOR $^{199}Hg^+$ FREQUENCY STANDARDS*

J.D. Miller, M.E. Poitzsch,† F.C. Cruz, D.J. Berkeland J.C. Bergquist, W.M. Itano, and D.J. Wineland
Time and Frequency Division, NIST
Boulder, Colorado 80303, USA

Abstract

A cryogenic linear rf trap has been constructed to study the accuracy of a clock based on laser cooled $^{199}Hg^+$. Crystals of tens of ions have been observed. The residual micromotion of the ions has been minimized and Ramsey interrogation periods of 25 s have been demonstrated for the 40.5 GHz transition. This system should eventually provide a frequency standard of high precision and accuracy. We report on the development of compact, efficient, solid-state sources at 194 nm and 282 nm for laser cooling of $^{199}Hg^+$ and investigation of the $^2S_{1/2} \rightarrow {}^2D_{5/2}$ quadrupole transition of interest for an optical frequency standard.

$^{199}Hg^+$ Atomic Clock System

Trapped, laser cooled ions are well suited to be the basis of future frequency standards. The use of trapped ions enables long interrogation times and high resolution. Reducing the kinetic energy of the trapped ions through laser cooling decreases systematic shifts to extremely small levels. To realize the advantages of trapped, laser cooled ions for frequency standards we have constructed a linear rf trap for the confinement of $^{199}Hg^+$ ions. A frequency standard based on the 40.5 GHz ground-state transition using 50 ions in this trap has a projected stability of $\sigma_y(\tau) = 5.5 \times 10^{-14}\tau^{-1/2}$.

The 40.5 GHz ground-state hyperfine transition of $^{199}Hg^+$ ions provides the basis for a high-performance frequency standard [1,2,3,4,5]. An rf-trapped $^{199}Hg^+$ ion frequency standard (using buffer gas cooling) has been demonstrated to have high frequency stability [3]. It contained $N \sim 2 \times 10^6$ ions and had a fractional second-order Doppler shift of $\sim -2 \times 10^{-12}$. Short-term fractional frequency stability of $< 7 \times 10^{-14}\tau^{-1/2}$ has been demonstrated in a linear trap geometry (also using buffer gas cooling) [4]. Operating with $N \sim 2.5 \times 10^6$ ions, they estimated a fractional second-order Doppler shift of $\sim -4 \times 10^{-13}$. In comparison, the fractional second-order Doppler shift of a single $^{199}Hg^+$ ion laser-cooled to the Doppler limit in an rf trap is -2.3×10^{-18} [5]. To improve the signal-to-noise ratio (and hence the fractional frequency stability), it would, however, be desirable to have multiple $^{199}Hg^+$ ions, all with equally low Doppler shifts.

Cryogenic Linear RF Ion Trap

The linear rf quadrupole trap, which uses four rf rods to achieve radial confinement and a static axial potential for longitudinal confinement, was developed as a way of confining multiple ions, all with the same low Doppler shift [6,7]. In this scheme, the four rods are configured as in an rf mass analyzer, with a zero-field node all along the centerline instead of at a single central point as in a conventional quadrupole Paul rf trap [8]. Axial confinement is achieved by applying static potentials at the ends of the trap, using positively biased rings, pins, or split sections in the trap rods. Recently, we [5] have demonstrated laser cooling in a linear rf trap in the small-N regime. In that apparatus, operating at room temperature in a vacuum of about 10^{-8} Pa, we were able to "crystallize" as many as several tens of $^{199}Hg^+$ ions at fixed positions in a single row along the trap's nodal centerline. Such a geometry is optimal for the present frequency standard application, since the ions can be imaged independently for improved signal-to-noise ratio, yet all have the same low second-order Doppler shift as a single ion in a quadrupole trap. The major limitation of this apparatus was the background gas pressure in the UHV chamber, which was still high enough that ions would be lost due to chemical reactions after times on the order of a few tens of minutes. At this pressure, pressure shifts could also limit the accuracy [9].

Our solution to the background gas pressure problem is to maintain the trap and vacuum vessel at liquid helium temperature (~ 4 K). At this low temperature, most gases cryopump to the walls of

*This work was supported by the ONR.
†Present address: Schlumberger-Anadrill, Sugar Land, TX 77478.

the chamber, giving a very low background pressure. In a similar sealed vacuum can, lowered to 4 K, Gabrielse *et al.* [10] report background pressures below 10^{-14} Pa. By thus lowering the pressure by several orders of magnitude, we should be able to store trapped ions for at least several days, interrogate them with Ramsey free-precession times as long as tens or hundreds of seconds, and be relatively insensitive to possible pressure shifts of the 40.5 GHz clock frequency. Operation of the trap at 4 K also reduces fractional shifts of the clock transition due to blackbody radiation to $< 1 \times 10^{-20}$ [11].

We have constructed and are testing a prototype apparatus based on these concepts. The trap is a small linear rf quadrupole, with four 0.40 mm diameter rods centered on a radius of 0.64 mm from the trap axis (about half the size of our previous trap [5]). Axial confinement is achieved with positively biased rings at either end of the four-rod quadrupole. The separation of the two rings is 4 mm. The trap and related apparatus are mounted in an indium-sealed OFHC copper vacuum can, inside a nested LHe/LN_2 dewar, heat-sunk to the outside bottom of the LHe reservoir. In addition to the trap, the vacuum vessel contains magnetic field coils, a miniature 40.5 GHz microwave antenna, a 5-element $f/1$ lens for 194 nm that can survive temperature cycling from 373 K to 4 K, and an HgO oven and a tungsten filament for loading ions into the trap. The trap is driven at 13 MHz with a few mW of rf using a superconducting helical resonator (immersed in the liquid helium) to step up the drive voltage to $\sim$ 100 V. Optical access to the trap region is through baffled windows around the base of the dewar. Magnetic shielding is achieved with conventional shields external to the liquid helium dewar.

Preliminary Results and Prospects

The trap and related apparatus are currently being tested. We can load and optically resolve individual cold ions, coalesced into linear crystals with inter-ion spacings of 10–30 μm. We have seen crystals ranging in number from one to several tens of ions. The rf micromotion of the ions has been minimized in three dimensions and crystals of tens of ions remain crystalized when the cooling beam is blocked for approximately 100 s. These crystals are very stable over periods of several hours when the cooling beam is on. We have seen no loss of ions from the trap while the ions are laser cooled, indicating that the background gas pressure is low. We have observed 20 mHz linewidths of the 40.5 GHz clock transition. Narrower linewidths should be possible with the use of a new 40.5 GHz source with higher resolution. With sufficient magnetic shielding, a fractional inaccuracy of $< 1 \times 10^{-16}$ appears attainable.

In addition, this apparatus should allow us to investigate new effects based on motional Zeeman coherences. These include a novel cooling scheme (proposed by Harde [12]) using optical pumping in conjunction with a motional magnetic coupling between the spin orientation and the harmonic oscillator state of the ions in the trap potential, as well as a scheme for "squeezing" the total ensemble spin, which could improve the signal-to-noise ratio in frequency standards where the dominant noise contribution is quantum fluctuations [13].

Solid-State 194 nm Source

Progress is being made toward an all solid-state source of 194 nm radiation which is needed to laser cool and optically detect mercury ions. Currently, the 194 nm light is generated by frequency doubling an argon-ion laser locked to a hyperfine component in iodine at 514.67 nm to obtain radiation at 257.34 nm. This is then sum frequency mixed with a stabilized diode laser operating at 790 nm. In the future, a frequency-doubled, compact, efficient, diode-pumped Yb:YAG laser that operates at 1.03 μm will replace the argon-ion laser [14]. More than 1 W of single frequency output has been obtained at 1.03 μm from the Yb:YAG laser pumped by three diode lasers. Each diode laser delivers about 1 W of power at 807 nm. We expect to double the Yb:YAG laser to 515 nm with greater than 50% efficiency [15].

Optical Frequency Standard

For the optical frequency standard based on the 282 nm $^2S_{1/2} \rightarrow ^2 D_{5/2}$ quadrupole transition in $^{199}Hg^+$, a quadrupled solid-state Nd:FAP laser at 1.126 μm is being developed. Single frequency efficiency at 1.126 μm of approximately 30%, when pumping with 807 nm, has been obtained. This laser will be frequency doubled to 563 nm in a monolithic cavity and then doubled again to 282 nm in a single-pass configuration. The better inherent frequency stability of a diode-pumped, all solid-state laser system should give a compact, reliable source for the optical local oscillator.

Acknowledgements

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