PROGRESS TOWARD A CRYOGENIC $^{199}Hg^{+}$ ION FREQUENCY STANDARD*

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Abstract

We have observed linear "crystals" of up to tens of laser-cooled $^{199}Hg^{+}$ ions in a new cryogenic linear rf ion trap that operates at liquid helium temperature and is designed for use as a prototype 40.5 GHz frequency standard with high accuracy and stability.

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

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]. The work at NIST on $^{199}Hg^{+}$ [5] has been devoted to obtaining a system that will provide high accuracy as well as high stability. To achieve this goal, we have incorporated laser cooling to suppress the second-order Doppler shift. In this paper, we report preliminary results using a cryogenic ($\sim$ 4 K) trap system. This should yield high vacuum, thereby reducing ion loss and frequency shifts due to background gas collisions, and should provide the basis for superconducting magnetic shielding.

At Hewlett-Packard [3] an rf-trapped $^{199}Hg^{+}$ ion frequency standard (using buffer gas cooling) has been demonstrated to have high frequency stability. It contained $N \sim 2 \times 10^{6}$ ions and had a fractional second-order Doppler shift of $\sim -2 \times 10^{-12}$. At JPL [4], 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). Operating with $N \sim 2.5 \times 10^{6}$ ions, they observed 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 is -2×10^{-18} [5]. The fractional frequency shift of the 40.5 GHz clock transition with magnetic field is $0.24B^{2}$, where B is expressed in teslas. Thus, a $^{199}Hg^{+}$ ion confined in an ion trap at near-zero magnetic field and laser-cooled to the Doppler limit should constitute a highly accurate 40.5 GHz microwave frequency standard, assuming sufficient magnetic shielding. 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 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 ($\sim$ 4 K). At this low temperature, most gases cryopump to the walls of 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. In addition, the 4 K temperature allows us to operate a superconducting shield around the ion trap region to help in shielding out changes in the magnetic field.

We have constructed and are testing a prototype apparatus based on the above 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 by positively biasing rings at either end of the four-rod quadrupole, whose separation 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 superconducting 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 field-emitter point 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 ~ 100 V. Optical access to the trap region is through baffled windows around the base of the dewar. The superconducting shield consists of a thin coating of lead, electroplated onto the inside of the copper vacuum vessel.

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. If left undisturbed, these crystals are very stable over periods of several hours. One rough measure of the background gas pressure is the rate at which trapped "impurity" ions of different species (which show up as non-fluorescing spots in the crystal) exchange places with their $^{199}Hg^+$ ion neighbors. This seems to occur very infrequently in our cryogenic vacuum. We hope to be able to demonstrate sub-hertz linewidths of the clock transition and assess the stability and accuracy of this frequency standard prototype.

Assuming a 10 s Ramsey interrogation time, the short-term fractional frequency stability of an ensemble of 20 ions could be $< 3 \times 10^{-13}\tau^{-1/2}$ if we succeed in detecting the ions independently and with nearly 100% detection efficiency. With sufficient magnetic shielding, a fractional inaccuracy of $< 1 \times 10^{-16}$ appears attainable.

In addition, this apparatus contains features (the superconducting coil pairs) that should allow us to investigate new effects based on motional Zeeman coherences. These include a novel cooling scheme (proposed by Harde [11]) 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 [12].

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