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

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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 100 s have been demonstrated for the 40.5 GHz transition. Systematic shifts to the clock transition due to magnetic field fluctuations as well as heating of the ions during the clock cycle have been evaluated. This system should eventually provide a frequency standard of high precision and accuracy.

$^{199}Hg^+$ 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 $\sim -4\times10^{-13}$. 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 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 ($\sim$ 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

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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 0.76 mm diameter BeCu tubes centered on a radius of 1.19 mm from the trap axis. Titanium wire (0.10 mm diameter) runs along the axis of the tubes and is insulated from the BeCu tubes with alumina tubes. The trap may be heated by passing current through the titanium wire. Heating the trap after loading is essential, as it removes Hg that is deposited on the trap during the loading procedure. Without this in-situ cleaning, contact potentials shift the minimum of the radial potential away from the nodal line of the rf trapping fields and prevent the formation of ion crystals. Titanium wire is chosen for its magnetic properties. 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 8 MHz with a $\sim$ 100 mW of rf using a copper 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 linear crystals ranging in number from one to several tens of ions. The strings are stable in the presence of the cooling beams, with no loss of ions observed while the laser cooling beams are on, indicating low background pressure. Ions have been kept without loss overnight without laser cooling, with one string of 13 ions remaining for one week of operation.

The rf micromotion of the ions has been minimized in three dimensions by correlating the fluorescence counts from the ions with the trap rf drive. Ion motion due to the rf trapping fields is detected as a modulation in the fluorescence counts due to the Doppler shift of ions moving toward and away from the laser cooling beams. Static potentials are added to bias rods to move the ion crystals toward the axis of the trap until this modulation is minimized.

For Hg ions cooled to the Doppler limit the second order Doppler is extremely small. However, the ions may heat due to interactions with the trapping fields when the cooling beams are turned off. This effect is potentially significant as the laser cooling beams are turned off during the interrogation of the clock transition for up to 100 s. The temperature of the ions was measured as a function of the time that the ions were left in the dark without laser cooling by measuring the Doppler width of the narrow S-D transition at 282 nm. No heating was observed for times of up to 100 s without laser cooling. Longer times were not attempted. The Doppler width of the S-D transition was 8 MHz, corresponding to an ion temperature $T < 20$ mK. The linewidth of the 282 nm laser was < 1 kHz and contributed a negligible amount to the measured width of the S-D line.

Magnetic shielding of the trap region is achieved through the use of high silicon content steel and mu-metal layers. These shields provide a dynamic shielding factor of 30. The magnetic field at the site of the ions after degaussing the shields is < 10 mG, and is currently reduced to $\sim$ 1 mG with coils inside the shields. The stability of the magnetic field has been measured by monitoring the $F = 0 \rightarrow F = 1, m_F = \pm 1$ tranisitions at 40 GHz over periods of time of several hours. Fluctuations in the magnetic field seen by the ions were measured to be $< 100\mu$G. Fluctuations in this frequency shift given the measured field stability correspond to a fractional inaccuracy of $< 5 \times 10^{-16}$. This could be further reduced with improved shielding and better cancellation of residual fields.

We have used a new 40.5 GHz source with

higher resolution to measure 5 mHz linewidths on the clock transition, corresponding to Ramsey interrogation times of 100 s. Evaluation of the clock stability has begun by locking the 40.5 GHz source to the ions for periods of time up to 2000 s with Ramsey interrogation times of up to 10 s. Longer averaging times and longer interrogation times will be used once tests of possible systematic shifts to the clock transition have been fully evaluated at the level obtained in these shorter runs.

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].

Acknowledgements

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References

[1] F.G. Major and G. Werth, Phys. Rev. Lett., Vol. 30, p. 1155, 1973.

[2] M.D. McGuire, R. Petsch, and G. Werth, Phys. Rev. A, Vol. 17, p. 1999, 1978.

[3] L.S. Cutler, R.P. Giffard, P.J. Wheeler, and G.M.R. Winkler, in Proc. 41st Ann. Symp. Freq. Control, p. 12, 1987.

[4] R.L. Tjoelker, J.D. Prestage, G.J. Dick, and L. Maleki, in Proc. 47th Ann. Symp. Freq. Control, p. 132, 1993.

[5] M.G. Raizen, J.M. Gilligan, J.C. Bergquist, W.M. Itano, and D.J. Wineland, Phys. Rev. A, Vol. 45, p. 6493, 1992.

[6] H.G. Dehmelt, in Frequency Standards and Metrology, ed. A. DeMarchi. Berlin: Springer, p. 286, 1989.

[7] J.D. Prestage, G.J. Dick, and L. Maleki, J. Appl. Phys., Vol. 66, p. 1013, 1989.

[8] W. Paul, O. Osberghaus, and E. Fischer, Forsch. Ber. des Wirtschaftsministeriums Nordrhein-Westfalen, Nr. 415, 1958.

[9] D.J. Wineland *et al.*, in Laser Manipulation of Atoms and Ions, ed. E. Arimondo, W.D. Phillips, and F. Strumia. Amsterdam: North-Holland, p. 553, 1992.

[10] G. Gabrielse *et al.*, in Atomic Physics 12, ed. J.C. Zorn and R.R. Lewis. New York: AIP, p. 549, 1991.

[11] W.M. Itano, L.L. Lewis and D.J. Wineland, Phys. Rev. A, Vol. 25, p. R1233, 1982.

[12] H. Harde, in Int. Conf. on Quantum Electronics Tech. Digest, Series 1990, Vol. 8. Washington, DC: OSA, p. 178, 1990.

[13] D.J. Wineland, J.J. Bollinger, W.M. Itano, F.L. Moore, and D.J. Heinzen, Phys. Rev. A, Vol. 46, p. R6797, 1992.