A 303-MHz Frequency Standard Based on Trapped Be^+ Ions

J. J. Bollinger, D. J. Heinzen, W. M. Itano, S. L. Gilbert, and D. J. Wineland

***Abstract*—A 303-MHz hyperfine transition in the ground state of $^9Be^+$ was used as a basis of a frequency standard. The ions were stored in a Penning ion trap. Linewidths as narrow as 900 μHz were obtained. The frequency stability was measured to be better than $3 \times 10^{-12}\tau^{-1/2}$. The inaccuracy in the second-order Doppler shift was reduced to 5 parts in 10^{15} by laser cooling. An apparent pressure shift with an unexpectedly large value was discovered which limits the accuracy of the current experiment to approximately 1 part in 10^{13}.**

I. Introducton

Ion traps provide the confinement with low perturbations necessary for improved frequency standards. For a microwave (or RF) frequency standard, typically many ions are stored in a trap in order to increase the signal-to-noise ratio and obtain good frequency stability. With many ions in a trap, the second-order Doppler shift is one of the largest systematic contributions to the inaccuracy of the standard [1]–[6]. In frequency standards which aim at high accuracy, the technique of laser cooling can be used to reduce the second-order Doppler shift to an acceptable level [1]–[3]. In this paper we investigated the use of Be^+ ions stored in a Penning trap to make a microwave (or RF) frequency standard with high accuracy. Be^+ is technically easy to trap and laser cool and, therefore, is a good candidate for investigating the use of stored ions as a microwave frequency standard. Other ions with even higher potential line Q's are discussed in [3].

Fig. 1 shows the energy level structure of the ground state of $^9Be^+$ as a function of the trap magnetic field B. At $B \simeq 0.8194$ T, the transition between levels 1 and 2, called the clock transition, depends only quadratically on magnetic field fluctuations and is, therefore, a suitable transition for a frequency standard. In this experiment, an oscillator is locked to this clock transition. The basic idea of this experiment has been described previously [7]–[10]. A description of the current experiment [10] is given below.

II. Experimental Technique

Between 5000 and 10 000 $^9Be^+$ ions and 50 000 to 150 000 $^{26}Mg^+$ ions were stored simultaneously in a cylindrical Penning trap [11] with $B \simeq 0.8194$ T under conditions of high vacuum ($\simeq 10^{-8}$ Pa). In order to minimize second-order Doppler shifts of the clock transition, the $^9Be^+$ ions were cooled to less than 250 mK by the following method. The $^{26}Mg^+$ ions were directly laser cooled and compressed by a narrow-band (~ 1 MHz) radiation source at 280 nm. The $^9Be^+$ ions were then sympathetically cooled [12] by their Coulomb interaction with the cold Mg^+ ions. A narrow-band 313-nm radiation source was used to optically pump and detect the $^9Be^+$ ions [13], [14]. Lenses were used to image the $^9Be^+$ fluorescence onto the photocathode of a photon-counting imaging detector. The overall detection efficiency was $\sim 2 \times 10^{-4}$. With the 313-nm source tuned to the $2s^2S_{1/2}(m_I = 3/2,\ m_J = 1/2)$ to $2p^2P_{3/2}(3/2,\ 3/2)$ transition, 94% of the $^9Be^+$ ions were optically pumped into the $2s^2S_{1/2}(3/2,\ 1/2)$ ground state. The 313-nm source was then turned off to avoid further optical pumping and ac Stark shifts. The sympathetic cooling of the $^9Be^+$ ions by the Mg^+ ions provided a steady cooling source independent of the 313-nm radiation and therefore permitted the use of long transition times.

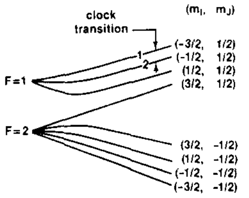

Fig. 1. Hyperfine energy levels (not drawn to scale) of the $^9Be^+$ 2s $^2S_{1/2}$ ground state as a function of magnetic field. At $B = 0.8194$ T the 303-MHz clock transition is independent of magnetic field to first order.

The clock transition was detected by the following method. After the 313-nm source was turned off, the ions in the $(3/2,\ 1/2)$ state were transferred to the $(1/2,\ 1/2)$ state and then to the $(-1/2,\ 1/2)$ state by two successive RF π pulses. Each pulse was 0.2-s long and resonant with the appropriate transition frequency (around 321 and 311 MHz, respectively). The clock transition was then driven by Ramsey's method of separated oscillatory fields with RF pulses of about 1-s duration and a free-precession time on the order of 100 s. Free-precession periods as long as 550 s were also used. This procedure transferred some of the ions from the $(-1/2,\ 1/2)$ state to the $(-3/2,\ 1/2)$ state. Those ions remaining in the $(-1/2,\ 1/2)$ state were then transferred back to the $(3/2,\ 1/2)$ state by reversing the order of the two RF π pulses. The 313-nm source was then turned back on, and the population of ions in the $(-3/2,\ 1/2)$ state was registered as a decrease in the $^9Be^+$ fluorescence, relative to the steady-state fluorescence, during the first second that the 313-nm source was on. The time for optical pumping from the $(-3/2,\ 1/2)$ state to the $(3/2,\ 1/2)$ state was approximately 10 s. After each measurement the system was reinitialized by leaving the 313-nm laser on for about 25 s.

III. Results

Fig. 2 shows the Ramsey signal obtained with a 550-s free precession period. The 900-μHz linewidth gives a line Q of 3.4

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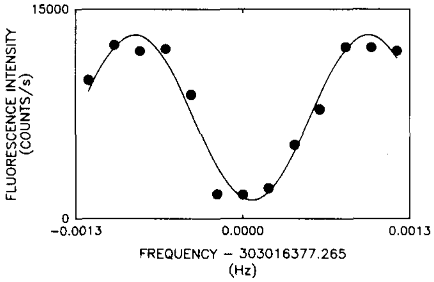

Fig. 2. Ramsey signal of the clock transition for a 550-s free precession period. The data are the result of one sweep (that is, one measurement per point). The sweep width is 2.4 mHz and the frequency interval between points is 0.2 mHz. The dots are experimental and the curve is a least-squares fit.

$\times 10^{11}$. Ramsey signals obtained with a 100-s free precession period were used to servo the frequency of a synthesized RF source [7]-[10]. Measurements were taken near the frequencies corresponding to the half minimum points on both sides of the center frequency. The difference in the measured signal strengths on either side of the line center was used by a computer to servo the average frequency of the synthesizer to the clock transition frequency. Most runs were taken with a commercial cesium beam clock (fractional frequency stability $\sigma_y(\tau) \simeq 6 \times 10^{-12}\tau^{-1/2}$ for measurement time τ in seconds) as the reference oscillator for the synthesizer, but a few runs were taken with a passive hydrogen maser ($\sigma_y(\tau) \simeq 2 - 3 \times 10^{-12} \tau^{-1/2}$) as the reference oscillator. The stability of the ^{9}Be$^+$ clock was measured to be better than $3 \times 10^{-12}\tau^{-1/2}$ for 10^3 s $\leq \tau \leq 10^4$ s, which is within a factor of 4 of the theoretical limiting stability for the number of ions used [3]. For $\tau \geq 10^6$ s the frequency stability was apparently limited by the pressure shift discussed below to $\sim 3 \times 10^{-14}$. The largest contribution to the second order Doppler shift was due to the $\vec{E} \times \vec{B}$ rotation of the ions about the axis of the trap. The rotation frequency and ion cloud radius were measured by using a weak laser beam to probe the ion cloud [13]. The fractional second-order Doppler shift was calculated to be $(-1.2 \pm 0.5) \times 10^{-14}$.

An apparent pressure shift more than three orders of magnitude larger than expected was discovered when the background gas pressure was increased. The background gas pressure could be increased by moving the magnet of the sputter ion pump which evacuated the trap region so that it overlapped fewer pumping cells and reduced the pumping speed. (We checked to make sure the magnetic field at the site of the ions was not disturbed. In addition, the shape and apparent temperature of the ion cloud could be monitored immediately before and after the Ramsey interrogation period from the image of the ion fluorescence. The increased background gas had a negligible effect on the cloud shape and temperature.) The composition of the gas was not known since the pressure was measured with a Bayard-Alpert gauge. However, when the vacuum vessel containing the trap was initially evacuated, the dominant background gases were H_2 and He. If the background gas was dominated by He, the fractional pressure shift was about -3×10^{-6} Pa^{-1}; if the background was dominated by H_2, the pressure shift was about -9×10^{-6} Pa^{-1}. Atomic ion hyperfine pressure shifts due to He have previously been measured in ^{137}Ba$^+$ [15] and in ^{199}Hg$^+$ [16] to be 5×10^{-11} Pa^{-1} and 4×10^{-11} Pa^{-1}, respectively. Vetter *et al.* [15] show that the long-range charge-induced interaction between the Ba$^+$ and the noble gas atoms gives one of the largest contributions to the pressure shift. Since this interaction depends primarily on the polarizability of the neutral atom we would expect that the pressure shift for He atoms on ^{9}Be$^+$ ions would not be significantly different than that for Ba$^+$ or Hg$^+$. Similarly, since the polarizability of H_2 is midway between Ar and Ne, we might expect the pressure shift for H_2 on Be$^+$ to be near those for Ar and Ne on Ba$^+$, which were measured to be -6×10^{-9} Pa^{-1} and -6×10^{-10} Pa^{-1}, respectively [15].

The apparent large discrepancy between our data and other measured pressure shifts is not understood at this time. One possible explanation is suggested by studies [17] of radiative association of C$^+$ with H_2 to form CH_2^+. In the models of this process, it is assumed that the H_2 can stick to the C$^+$ for a long enough time to allow the C$^+$$-H_2$ complex to radiatively stabilize. This sticking is possible because the collision energy can be taken up by the internal degrees of freedom in the H_2 molecule. The sticking time can be orders of magnitude longer than the interaction time during a simple elastic collision. If a similar sticking mechanism is active in H_2 – Be$^+$ collisions, it may account for the apparent large pressure shift. We plan to check this hypothesis by measuring the pressure shifts of Be$^+$ on Ne and Ar, where the sticking would not be expected to occur, and on H_2, where sticking might occur.

If the apparent collisional shift is real, the background pressure of 10^{-8} Pa in this trap will limit the accuracy of the Be$^+$ clock to about 1 part in 10^{13}. We are continuing to search for other causes of systematic error such as electronic offsets. We feel the accuracy could be improved beyond 5 parts in 10^{15} in the future. It may be necessary to use liquid He cryopumping to reduce the background pressure.

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