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
National Institute of Standards and Technology
325 Broadway, Boulder, Colorado 80303

Abstract

A 303-MHz hyperfine transition in the ground state of Be^+ ions stored in a Penning trap was used as a basis of a frequency standard. Linewidths as narrow as 900 μHz were obtained. The inaccuracy in the second order Doppler shift was reduced to 5 parts in 10^{15} by laser cooling.

Summary

Figure 1 shows the energy level structure of the ground state of $^9Be^+$ in the presence of an applied 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.

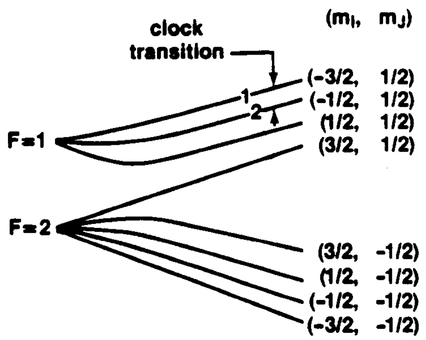

FIG. 1 Hyperfine energy levels (not drawn to scale) of the $^9Be^+$ 2s $^2S_{1/2}$ ground state as a function of magnetic field. At B = 0.8194 T the 303-MHz clock transition is independent of magnetic field to first order.

Between 5000 and 10 000 $^9Be^+$ ions and 50 000 to 150 000 $^{26}Mg^+$ ions were simultaneously stored in a cylindrical Penning trap[1] with $B \simeq 0.8194$ T under conditions of high vacuum ($\lesssim 10^{-8}$ Pa). To minimize second-order Doppler shifts of the clock transition, the $^9Be^+$ ions were cooled to less than 250 mK. The $^{26}Mg^+$ ions were directly laser cooled and compressed by a narrowband (~1 MHz) radiation source at 280 nm. The $^9Be^+$ ions were then sympathetically cooled[2] by their Coulomb interaction with the cold Mg^+ ions. A narrowband 313-nm radiation source was used to optically pump and detect the $^9Be^+$ ions.[3] 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 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.

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 used. This 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.

Figure 2 shows the Ramsey signal obtained with a 550 s free precession period. The 900 μHz linewidth gives a line Q of 3.4×10^{11}. Ramsey signals obtained with a 100 s free precession period were used to steer the frequency of a synthesized rf source. The fractional frequency stability $\sigma_y(\tau)$ of the stabilized rf was measured to be better than $\sigma_y(\tau) \sim 3\times10^{-12}\tau^{-\frac{1}{2}}$ for measurement times $\tau \lesssim 3\times10^4$ s. The measurement was limited by the available reference oscillator. The largest contribution to the second order Doppler shift is 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. The fractional second order Doppler shift was calculated to be $(-1.2\pm0.5)\times10^{-14}$.

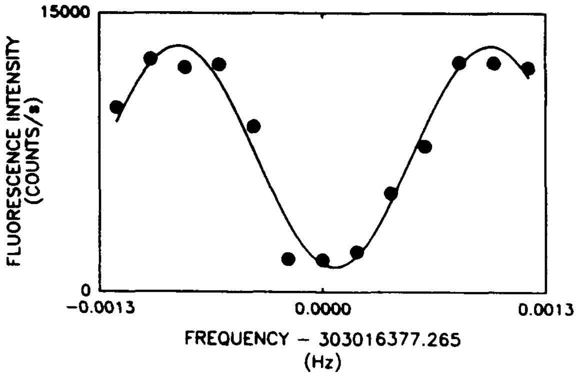

FIG.2 Ramsey signal of the clock transition for a 550 s free precession period. The data are the result of one sweep (that is, one measurement per point). The sweep width is 2.4 mHz and the frequency interval between points is 0.2 mHz. The dots are experimental and the curve is a least-squares fit.

One source of systematic uncertainty was discovered which was larger than the uncertainty in the second order Doppler shift. We measured an increase in the Be^+ clock transition frequency as the background pressure was increased. This shift could be as large as $+2\times10^{-13}$ for each 10^{-8} Pa ($\sim10^{-10}$ Torr) pressure increase, although our measurement of the absolute pressure at the trap is uncertain. With a background pressure of 10^{-8} Pa, the accuracy of our measured Be^+ clock transition frequency was therefore $\sim 1\times10^{-13}$. Pressure shifts due to noble gas collisions should be 3 orders of magnitude less than this.[4] The surprisingly large shift may be due to collisions with background H_2 molecules, for which there has been no experimental or theoretical work.

References

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