# Precision Measurements of Laser Cooled $^9Be^+$ Ions

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## 1. Introduction

The long confinement times with minimal perturbations of ion storage techniques provide a basis for high resolution spectroscopy [1,2]. Line Q's greater than $10^{10}$ and linewidths smaller than a few Hz have been obtained on ground-state hyperfine transitions in atomic ions stored in rf quadrupole traps [3-7]. The accuracy of these measurements has been limited, to a large extent, by the second-order Doppler shift. Radiation pressure from lasers has been used to reduce the second-order Doppler shift by cooling ion temperatures below 1 K for single $Ba^+$ and $Mg^+$ ions in an rf trap [8,9] and for single $Mg^+$ ions and small clouds of $Mg^+$ ions in a Penning trap [10-12]. $^9Be^+$ ions have an electronic structure similar to $Mg^+$ ions and are consequently easy to cool with a frequency-doubled dye laser ($\lambda$=313 nm). This paper discusses measurements of cyclotron frequencies, g-factors, hyperfine constants, and ion cloud parameters which have been made on clouds of laser-cooled $^9Be^+$ ions.

The $^9Be^+$ ions are confined by the static magnetic and electric fields of a Penning trap and stored for hours. The trap is made of gold mesh endcaps and a molybdenum mesh ring electrode. The center of the trap is at one focus of an ellipsoidal mirror; the second focus is outside the vacuum system. A lens is used to collimate the fluorescence light into a photomultiplier tube. The ions are cooled and compressed by a 313 nm narrowband source tuned to the $2s^2S_{\frac{1}{2}}$ $(M_I,M_J)=(-3/2,-1/2) \rightarrow 2p^2P_{3/2}$ $(-3/2,-3/2)$ transition. The 313 nm light source is obtained by generating the second harmonic of the output of a single mode cw dye laser in a 90° phase-matched crystal of rubidium dihydrogen phosphate (RDP). The resulting power is typically 20 μW. In addition to cooling, the 313 nm light also optically pumps the ions into the $(M_I,M_J)=(-3/2,-1/2)$ ground state [10,11].

## 2. Laser-Fluorescence Mass Spectroscopy

The axial ($\nu_z$), magnetron ($\nu_m$), and electric-field-shifted cyclotron ($\nu_c'$) frequencies of a small cloud of $^9Be^+$ ions stored in a Penning trap are measured by observing the changes in ion fluorescence scattering from the laser beam which is focused onto the ion cloud [13]. When the ion motional frequencies are excited by an externally applied oscillating electric field, the ion orbits increase in size, causing a decrease in laser fluorescence due to a decrease in overlap between the ion cloud and laser beam. To a good approximation, the electric field excites only the collective center-of-mass modes, whose frequencies are equal to those of a single, isolated ion in the trap [14]. The three measured frequencies can then be combined to yield the free-space cyclotron frequency ($\nu_c$) from the expression [15]

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$$qB_0/2\pi m = \nu_c = [(\nu_c')^2 + \nu_z^2 + \nu_m^2]^{\frac{1}{2}} \qquad (1)$$

where $B_0$ is the applied magnetic field, q is the ion charge, and m is the ion mass. Mass comparisons can be made by measuring $\nu_c$ for different ions.

This technique was demonstrated by comparing the cyclotron frequency to magnetic-field-dependent nuclear-spin-flip hyperfine $|\Delta M_I| = 1$ transition frequencies in the $^9Be^+$ ground state. This, along with the Breit-Rabi formula, yielded the ratio [13]

$$R = g_J(^9Be^+)m(^9Be^+)/m_e \qquad (2)$$

to 0.15 ppm. This result, with a theoretical value of $g_J(^9Be^+)$ [16] and the known value [17] of $m(^9Be^+)/m_p$, can be used to give an indirect determination of $m_p/m_e$,

$$m_p/m_e = 1836.152\ 38(62)\ (0.34\ \text{ppm}) \qquad (3)$$

This value agrees with the most precise direct determination [18]. If the recent value of $m_p/m_e$ from Ref. 18 is used, an indirect determination,

$$g_J(^9Be^+) = 2.002\ 262\ 63\ (33)\ (0.16\ \text{ppm}), \qquad (4)$$

is obtained which agrees with the theoretical calculations [16]. Because of the small cloud sizes and small excitation required to observe the motional resonance, the potential accuracy of the laser fluorescence method for mass spectroscopy is extremely high due to suppression of field inhomogeneity and trap anharmonicity effects. It is estimated that ion cyclotron resonance accuracies near 1 part in $10^{13}$ may ultimately be possible [13].

## 3. Cloud Temperature, Density, and Size

The cloud temperature, density, and size can be determined by using a second focused, frequency-doubled dye laser as a probe laser. If the probe laser is tuned from the optically pumped (-3/2,-1/2) ground state to the $2p^2P_{3/2}$ (-3/2,+1/2) state, some of the ion population is removed from the (-3/2,-1/2) ground state. This results in a decrease in the fluorescence light intensity. The size of this signal depends on the overlap of the probe beam with the cloud. The spatial extent of the cloud can be determined by measuring where the depopulation transition signal disappears as the probe laser is moved across the cloud. In this way the shape of the clouds is measured to be approximately ellipsoidal with typical dimensions ranging from 100 to 300 μm.

The ion cloud undergoes a slow $\vec{E} \times \vec{B}$ drift rotation about the z axis. The cloud rotation frequency differs from the single ion magnetron frequency due to the space charge of the other ions. It can be determined by measuring the change in the Doppler shift of the depopulation transition as the probe laser is moved in the radial direction. The ion number density is then obtained from the measured cloud rotation frequency. Measured densities are $1\text{-}2\times10^7$ ions/cm³ and are relatively independent of the number of ions in the cloud, the trap voltage, and other trap parameters. For the small and large cloud sizes, this gives total ion numbers ranging from a few ions to nearly 1000 ions.

The temperature of the cyclotron motion can be determined from the full width at half maximum (fwhm) of the depopulation transition. Cyclotron temperatures of 20 to 100 mK were obtained for almost all of the clouds. From the measurements of the cloud size and rotation frequency, the magnetron kinetic energy averaged over the cloud can be determined and an effective magnetron temperature can be calculated. This temperature increases with the size of the cloud, but even for the larger clouds, it is less than 200 mK. Because the probe laser is directed perpendicular to the magnetic field, a direct measurement of the axial temperature cannot be made. The axial motion is indirectly cooled by collisional coupling to the cyclotron motion but is directly heated by the recoil of the scattered photons [19]. The equilibration time between the axial and cyclotron motions is determined to be less than 100 ms for the clouds in this experiment. The axial temperature is measured by turning off the cooling laser, waiting a variable length of time, and then measuring the temperature of the cyclotron motion. In this way axial temperatures are measured to be hotter than typical cyclotron temperatures, but not more than 200 to 300 mK for most of the clouds. A typical average temperature of 200 mK gives a second-order Doppler shift of 3 parts in $10^{15}$.

In a frame of reference rotating with the cloud, the ion cloud behaves like a one-component plasma; that is, the positive charged ions behave as if they were moving in a uniform density background of negative charge [20]. The properties of such a plasma are determined by the coupling constant $\Gamma$. $\Gamma$ equals the potential energy of nearest neighbors divided by the thermal energy of the ions. For $\Gamma$'s approaching 1, the plasma is called strongly coupled. Theoretical calculations predict that for $\Gamma>2$, the plasma should have characteristics associated with those of a liquid, and at $\Gamma \approx 155$, a liquid-solid phase transition should take place [21]. We have measured $\Gamma$'s on the order of 3 or 4 for many clouds and as high as 10-15 for a few clouds. It may eventually be possible to obtain $\Gamma$'s where an ordering of the cloud into a lattice structure may take place [22].

## 4. Hyperfine Structure Measurements

By measuring the frequency difference between depopulation transitions when the probe laser is tuned to different $2p^2P$ states, a determination of the $2p^2P_{1/2}$ hyperfine structure and the $2p^2P$ fine structure separation is made [23]. The $2p^2P_{1/2}$ A value is determined to be -114.4(6.0) MHz. This is the first experimental measurement of the $2p^2P_{1/2}$ A value and it is in agreement with the theoretical calculation of -116.8(2.4) MHz [24]. The zero field $2p^2P_{1/2}$ - $2p^2P_{3/2}$ fine structure interval is determined to be 197.151(75) GHz. In addition, the zero field $2p^2P_{3/2} \leftarrow 2s^2S_{1/2}$ and $2p^2P_{1/2} \leftarrow 2s^2S_{1/2}$ optical transitions are determined to be 31 935.3198(45) $\mathrm{cm}^{-1}$ and 31 928.7435(40) $\mathrm{cm}^{-1}$ respectively.

The ground state hyperfine structure is determined by measuring the $(-3/2,1/2) \rightarrow (-1/2,1/2)$ and $(3/2,-1/2) \rightarrow (1/2,-1/2)$ ground state transition frequencies at magnetic field independent points [11] (see Fig. 1). Microwaves are used to transfer population from the optically pumped ground state to one of the states of a field independent transition. The transition is detected by a decrease in the fluorescence light intensity when the field-independent transition is probed. Figure 2 shows the signal obtained for the $(-3/2, 1/2) \rightarrow (-1/2,1/2)$ transition. The oscillatory lineshape results from the use of the Ramsey interference method, which is implemented by driving the transition with two coherent rf pulses of 0.5 s duration separated by 19 s. The performance of an

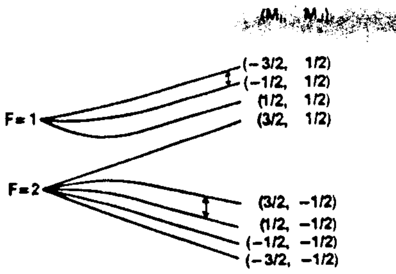

Figure 1. Hyperfine structure of the $^9Be^+$ $2s^2S_{\frac{1}{2}}$ ground state as a function of magnetic field. Two field-independent transitions at 0.68 and 0.82 T are shown

oscillator locked to this transition is measured [25] to be comparable to the performance of a commercial Cs standard. In addition, the (-3/2,1/2) → (-1/2,+1/2) field independent transition frequency is determined to 4x10$^{-13}$ accuracy. Work on the (3/2,-1/2)→(1/2,-1/2) field-independent transition is not completed, but preliminary measurements have determined its frequency to 4x10$^{-12}$ accuracy. From these two measurements, preliminary ground-state values of A= -625 008 837.048(4) Hz (6x10$^{-12}$) and $g_I/g_J$= 2.134 779 853(1)x10$^{4}$ (5x10$^{-10}$) are obtained.

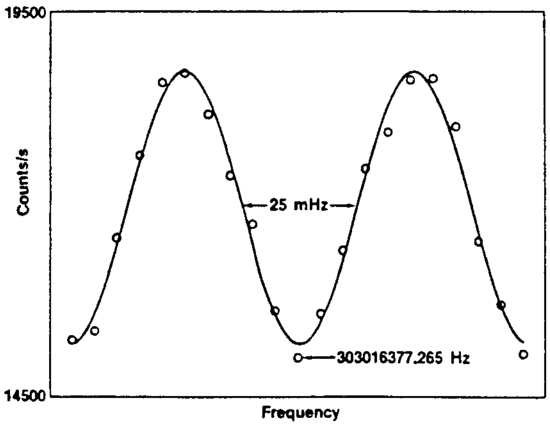

Figure 2. Signal obtained on the (-3/2,1/2)→(-1/2,1/2) field-independent transition. The sweep width is 100 mHz and the frequency interval between points is 5 mHz. The dots are experimental and are the average of ten sweeps; the curve is a least-squares fit

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