LASER-COOLED STORED ION EXPERIMENTS USING PENNING TRAPS

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Abstract

Small clouds of ^{9}Be$^+$ ions are stored in a Penning trap and cooled with a laser to temperatures below 200 mK. The ions are detected by their fluorescence induced by the cooling laser. Experiments on high resolution spectroscopy and frequency standards, mass spectroscopy, and one-component plasmas are discussed.

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 hertz 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[8-12]. Work at NBS has concentrated on cooling clouds of ions in Penning-type traps because of its potential application to improved atomic clocks[13,14]. ^{9}Be$^+$ ions are experimentally easy to cool with a laser and therefore are good candidates for studies of generic properties of laser-cooled ions.

The ^{9}Be$^+$ 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 photmultiplier tube. The ions are cooled and compressed by a 313 nm narrowband source tuned to the $2s\,^2S_{1/2}\ (M_I,M_J)=(-3/2,-1/2) \rightarrow 2p\,^2P_{3/2}\ (-3/2,-3/2)$ 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].

Laser-Fluorescence Mass Spectroscopy

The axial (ν_z), magnetron (ν_m), and electric-field-shifted cyclotron (ν_c') frequencies of a small cloud of ^{9}Be$^+$ 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[15]. 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[16]. The three measured frequencies can then be combined to yield the free-space cyclotron frequency (ν_c) from the expression[17],

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

where B_o is the applied magnetic field, q is the ion charge and m is the ion mass. Mass comparisons can be made by measuring ν_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 ^{9}Be$^+$ ground state. This, along with the Breit-Rabi formula, yielded the ratio[15]

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

to 0.15 ppm. This result, with a theoretical value[18] of $g_J(^9\mathrm{Be}^+)$ and the known value[19] of $m(^9\mathrm{Be}^+)/m_p$, can be used to give an indirect determination of the proton-to-electron mass ratio,

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

This value agrees with the most precise direct determination[20]. Using the recent value of m_p/m_e from Ref. 20, we obtain an indirect determination of the ^{9}Be$^+$ ground state g factor,

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

which agrees with the theoretical calculations[18]. 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. For single ions, it is estimated that ion cyclotron resonance accuracies near 1 part in 10^{13} may ultimately be possible[15].

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 induced by the cooling laser. 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 in these experiments 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/cm^3 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, we can determine the magnetron kinetic energy averaged over the cloud and calculate an effective magnetron temperature. This temperature increases with the size of the cloud, but even for the larger clouds it is less than 200 mK. The axial motion is indirectly cooled by collisional coupling to the cyclotron motion but is directly heated by the recoil of the scattered photons[21]. Consequently the axial temperature could be higher than the cyclotron temperature. Recently we modified the trap to permit a direct measurement of the axial temperature by passing the probe beam along the diagonal between the ring and the endcaps. Axial temperatures less than 150 mK were measured. A temperature of 200 mK gives a second-order Doppler shift of 3 parts in 10^{15} for $^9Be^+$ ions.

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[22]. The properties of such a plasma are determined by the coupling constant Γ. Γ equals the potential energy of nearest neighbors divided by the thermal energy of the ions. For Γ'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 $\Gamma\cong155$, a liquid-solid phase transition should take place[23]. We have measured Γ's on the order of 4 to 10 for the clouds of this experiment. It may eventually be possible to obtain Γ's where an ordering of the cloud into a lattice structure may take place.

Ground-State Hyperfine Structure

The ground-state hyperfine structure is determined by measuring the (-3/2,1/2) → (-1/2,1/2) and (3/2,-1/2) → (1/2,-1/2) ground-state transition frequencies at magnetic field independent points[11] (see Fig. 1). Microwaves 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) → (-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 oscillator locked to this transition is measured[24] to be comparable to the performance of a commercial Cs standard. In 25 hours, a precision of 1.5 parts in 10^{13} is obtained. The largest anticipated systematic error is due to the second-order Doppler shift. With the cooling laser on continuously, second-order Doppler shifts of 3 parts in 10^{15} are measured. When the laser is turned off, a residual heating of the ions is observed. Over the 20 s interval the cooling laser is turned off, the heating raises the ion temperature to a few kelvin and the second-order Doppler shift to on the order of 5×10^{-14}. A check for unknown systematic errors was made by varying different experimental parameters. Nothing was observed at a level permitted by the signal-to-noise. We determined the (-3/2,1/2) → (-1/2,+1/2) field independent transition frequency to 4×10^{-13} accuracy. This is comparable to the accuracy of laboratory cesium beam clocks. 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 4×10^{-12} accuracy[12]. From these two measurements, preliminary ground state values of $A = -625\ 008\ 837.048(4)$ Hz (6×10^{-12}) and $g_I/g_J = 2.134\ 779\ 853(1)\times10^{-4}$ (5×10^{-10}) are obtained.

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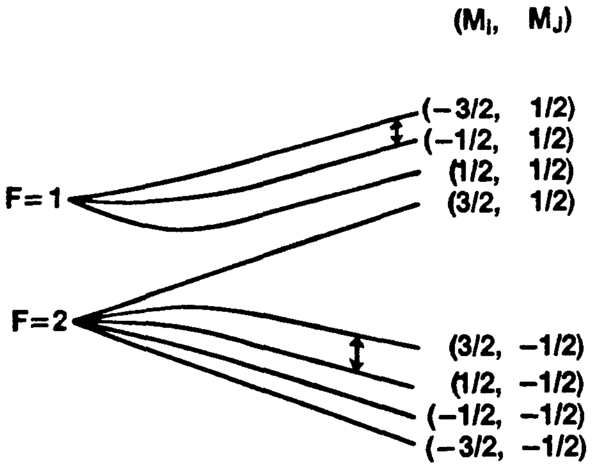

Figure 1. Hyperfine structure of the $^9Be^+$ $2s\,^2S_{1/2}$ ground state as a function of magnetic field. Two field independent transitions at 0.68 and 0.82 T are shown.

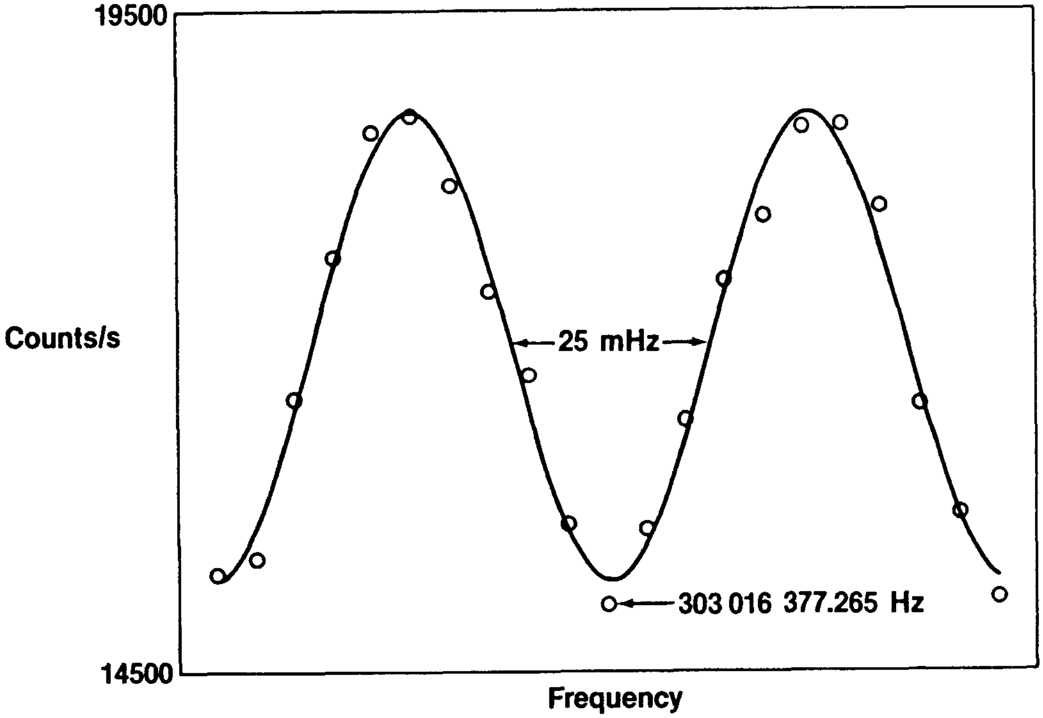

Figure 2. Signal obtained on the (-3/2,1/2) → (-1/2,1/2) field independent transition. The sweep width is 100 MHz and the frequency interval between points is 5 MHz. The dots are experimental and are the average of 10 sweeps; the curve is a least squares fit.

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