SPECTROSCOPY OF A SINGLE Mg^+ ION ☆

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A single $^{24}Mg^+$ ion has been laser cooled in a Penning trap and its optical spectrum observed by a double resonance technique. Residual Doppler line broadening implies a cyclotron–magnetron temperature of 50 ± 30 mK.

Laser cooling of ions bound in electromagnetic traps was first demonstrated [1] in 1978. More recently, this technique has been used in experiments that detect the fluorescence of, photograph, and observe a Raman transition on a single, laser-cooled Ba^+ ion in an RF trap [2]. This ability to localize single cold particles approaches the experimentalist's ideal of obtaining unperturbed systems at rest. In this letter, we report the isolation and double resonance detection [3] of a single, laser-cooled Mg^+ ion in a Penning trap. The primary differences of this work from that of ref. [2] are: (1) the requirements for localization and cooling of an ion in a Penning trap are substantially different than for the case of the RF trap, (2) we derive a kinetic "temperature" for the ion from the measured Doppler broadening of the optical spectrum rather than from the cloud size, (3) the intensity of fluorescence from a single ion is determined by destruction of individual ions by charge exchange rather than by creation by ionization.

The basic configuration of the experiment has been described elsewhere [1,3,4]. Briefly, in the present experiments, approximately three $^{24}Mg^+$ ions are loaded into the trap ($V_0 \approx 2$ V, $B_0 \approx 1$ T), laser cooled, and localized [4] at the center of the trap. V_0 and B_0 are the applied static trap potential and magnetic field. The laser beam (power approximately 5 μW) is weakly focused near the center of the trap to spot size $w_0 \approx 25$ μm and is incident at an angle $\theta = 82°$ with respect to the $\hat{z}$ (B field) axis. This provides both axial and radial laser cooling. Typically, the laser beam is positioned approximately 15 μm radially from trap center in a direction such that the magnetron velocity is in the same direction as the laser beam. Typical detuning of the laser frequency is about −25 MHz from the non-Doppler-shifted $(3p\ ^2P_{3/2}, M_J = -3/2) \leftarrow (3s\ ^2S_{1/2}, M_J = -1/2)$ $^{24}Mg^+$ transition. This combination of frequency detuning and spatial positioning ensures both magnetron and cyclotron cooling [4].

Fluorescence from the $^{24}Mg^+$ ions is observed while a ^{25}Mg oven is heated at a low level and the resulting atomic beam directed at the $^{24}Mg^+$ ions. The fluorescence is observed to decrease as a function of time as shown in fig. 1. We attribute the step decreases in fluorescence intensity to the occurrence of single charge exchange events ($^{24}Mg^+ + {}^{25}Mg \rightarrow {}^{24}Mg + {}^{25}Mg^+$) eliminating the $^{24}Mg^+$ ions, one at a time. The trapped $^{25}Mg^+$ ions are ejected from the trap in about 0.2 s by cyclotron–magnetron RF excitation.

We note that the steps are of unequal size, but this is not unexpected since the magnitude of the fluorescence will depend on the spatial overlap of the ions and laser beam (which depends on ion number) and the magnetron Doppler shift, which depends on the Coulomb interaction between ions as well as applied trap voltage. We also remark that fig. 1 is *not* a "typical" curve because it shows only charge exchange events. Elastic collisions ($^{24}Mg^+ + {}^{25}Mg \rightarrow {}^{24}Mg^+ + {}^{25}Mg$) can also be observed. These are indicated by a sudden drop

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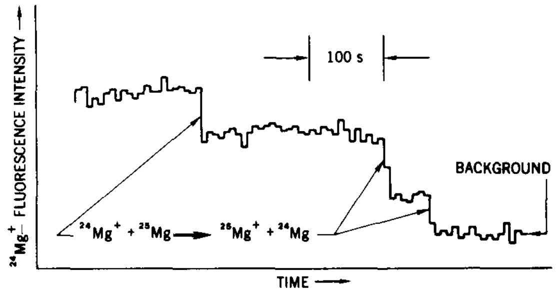

Fig. 1. $^{24}Mg^+$ ion fluorescence versus time when a ^{25}Mg atomic beam is directed at trap center. Fluorescence is integrated for 10 s on each experimental point. The large steps are attributed to single charge exchange events ($^{24}Mg^+ + ^{25}Mg \rightarrow ^{24}Mg + ^{25}Mg^+$) which remove the $^{24}Mg^+$ ions, one at a time. The last plateau is due to a single $^{24}Mg^+$ ion at trap center.

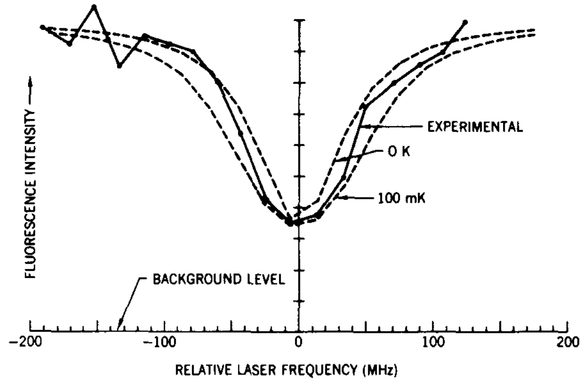

Fig. 2. Double resonance curve of a single $^{24}Mg^+$ ion. On the vertical axis is the fluorescence from a fixed frequency laser (power approximately 5 μW) tuned to the $(^2P_{3/2}, M_J = -3/2) \leftarrow (^2S_{1/2}, M_J = -1/2)$ transition. Each point represents a 10 s integration; the connecting lines are only for clarity. The horizontal axis is the frequency of the low-power ($\ll 5$ μW) laser which is continuously scanned across the $(^2P_{3/2}, M_J = -1/2) \leftarrow (^2S_{1/2}, M_J = -1/2)$ transition. The dashed curves are simulations of fluorescence at $T = 0$ K and 100 mK (no added noise). The solid curve is experimental data. From these data, we conclude $T = 50 \pm 30$ mK.

in fluorescence (a step down) as a $^{24}Mg^+$ ion is heated by the collision, causing its fluorescence to decrease due to its large Doppler width and orbit sizes. However, after some time (up to a few hundred seconds), it is again cooled down and localized at trap center and we see a step increase in the fluorescence to the former value. More important, one might suspect that the steps could be due to two or more ions: i.e., one $^{24}Mg^+$ ion is removed by charge exchange and during the time the $^{25}Mg^+$ ion is still in the trap, it has some probability (although estimated to be very small) that it heats the remaining $^{24}Mg^+$ ions by Coulomb collisions.

Since the goal of the experiment was to observe a single $^{24}Mg^+$ ion, the above difficulties could be avoided as follows: The $^{24}Mg^+$ loading conditions were scaled down so that after careful searching, fluorescence was observed on only 20% of the loads. Statistically, this meant that if any fluorescence was observed, it was, with high probability, from a single ion. At this time, the double resonance experiments (described below) were performed, after which, we looked for a single step after the ^{25}Mg oven was turned on. Immediately after this step was observed, the ^{25}Mg oven was turned off and a careful search was made to find any remaining $^{24}Mg^+$ ions. Since none were found, we concluded that, with high probability, we had a single ion.

The features of the optical spectrum of a single ion (fig. 2) could be recorded by using a simple optical pumping, double resonance scheme [3]. Briefly, a "high-power" laser (power approximately equal to 5 μW) is used to keep the ion cold and at trap center; this laser also optically pumps the ion [3] so that it spends about 94% of its time in the $(^2S_{1/2}, M_J = -1/2)$ ground state Zeeman sublevel and about 6% of its time in the $(^2S_{1/2}, M_J = +1/2)$ level. If the frequency of a second lower-power ($\leqslant 5$ μW) laser beam (coincident spatially with the first laser beam) is swept through the $(^2P_{3/2}, M_J = -1/2) \leftarrow (^2S_{1/2}, M_J = -1/2)$ transition, the resonance condition will be indicated by a decrease in fluorescence due to the first laser. Specifically, the observed fluorescence is proportional to the fraction of time, $f_{-1/2}$, the ion spends in the $(M_J = -1/2)$ ground state sublevel, which is approximately equal to

$$f_{-1/2} = \tfrac{16}{17}[1 + 8R_1/(17R_2)]^{-1}\,, \qquad (1)$$

where R_1 is the $(^2P_{3/2}, M_J = -1/2) \leftarrow (^2S_{1/2}, M_J = -1/2)$ transition rate, due to the low-power laser, and R_2 is the $(^2P_{3/2}, M_J = -1/2) \leftarrow (^2S_{1/2}, M_J = +1/2)$ transition rate, due to off-resonance scattering by the high-power laser. This method is superior to a previous method [4], since the signal is due to the higher scattering by the high-power laser; also the ion temperature is not significantly perturbed by the low-power laser. The experimental resonance curve in fig. 2 can be compared to the two other curves which were simulated,

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assuming the ion kinetic energy had a Maxwell–Boltzmann distribution in time. The width of the 0 K curve is due to the 43 MHz natural width [5]. It is slightly broadened because of the detailed nature of the fluorescence intensity as given by eq. (1) and because the laser is continuously swept during the integration period. It is slightly asymmetric since the integration periods are not symmetric about line center. From this kind of data, we conclude that the cyclotron–magnetron "temperature" was 50 ± 30 mK. The axial temperature, T_z, can be estimated by lowering the axial well depth by lowering V_0 and noting the decrease in fluorescence as the axial excursions become comparable to the laser spot size. With V_0 = 1 V, the fluorescence signal drops to about half its value for $V_0 \approx 7$ V, which implies $T_z \approx 600$ mK. The Doppler broadening information is relatively insensitive to the axial temperature because θ is close to 90°. Assuming the cyclotron–magnetron temperature is zero, this yields an axial temperature of 2.6 ± 1.5 K. Thus, we conclude that the Doppler broadening is primarily a measure of cyclotron–magnetron temperature. We also note that experimentally, for a single ion, the radial extent is significantly less than the laser spot diameter.

Cyclotron–axial cooling and magnetron "cooling" in a Penning trap are fundamentally different in nature. Here, cooling is defined as reducing the *kinetic* energy in the three (cyclotron, axial, and magnetron) degrees of freedom. Previous treatments [6] apply to the harmonic axial motion. If we define the potential energy to be zero at trap center, then we can write the total energy (kinetic and potential) in the magnetron and cyclotron degrees of freedom as

$$E_\mathrm{m} = \tfrac{1}{2}Mr_\mathrm{m}^2(\omega_\mathrm{m}^2 - \tfrac{1}{2}\omega_z^2)\,,$$
$$E_\mathrm{c} = \tfrac{1}{2}Mr_\mathrm{c}^2(\omega_\mathrm{c}'^2 - \tfrac{1}{2}\omega_z^2)\,, \qquad (2)$$

where

$$\omega_z^2 = 4eV_0/M(r_0^2 + 2z_0^2)\,, \qquad (3)$$

ω_m, ω_c', and ω_z are the magnetron, cyclotron, and axial frequencies and r_m and r_c are the magnetron and cyclotron radii. The dependence of the potential energy [second terms in eq. (2)] on the applied trap potential V_0 and trap dimensions r_0 and z_0 is apparent in eq. (3). Since $\omega_\mathrm{m} < \omega_z/\sqrt{2} < \omega_\mathrm{c}'$ for trapping, then $E_\mathrm{c} > 0$, but $E_\mathrm{m} < 0$. To reduce r_m and thereby the magnetron kinetic energy, we must therefore increase the total magnetron energy. Conversely, to reduce r_c and thereby the cyclotron kinetic energy, we must *decrease* the total cyclotron energy. (The cyclotron case is analogous to the harmonic binding case described in ref. [6].) If we view laser scattering events as point interactions (valid since $\omega_z, \omega_\mathrm{m}, \omega_\mathrm{c}' \ll \gamma$, where γ is the optical linewidth) then the requirements for cooling are that we preferentially scatter photons when the magnetron motion recedes from the laser and the cyclotron motion approaches the laser. Since the direction of circulation is the same for both degrees of freedom, it might appear that these conditions cannot simultaneously be satisfied, but they can if the laser intensity is higher on the side of trap center where the magnetron motion recedes from the laser [4,7]. This is accomplished in our experiments by working on the slope of the nearly gaussian laser beam profile.

We have theoretically modeled the cooling of a single ion in a Penning trap [7], and when applied to our experimental conditions, these calculations can be used to predict minimum temperatures. If we define

$$T_\mathrm{m} = M\omega_\mathrm{m}^2 r_\mathrm{m}^2/(2k)\,, \qquad T_\mathrm{c} = M\omega_\mathrm{c}'^2 r_\mathrm{c}^2/(2k)$$
$$T_z = M\langle v_z^2\rangle/k\,,$$

where k is Boltzmann's constant, then we find minimum temperatures $T_\mathrm{m} \approx 1.3 \times 10^{-6}$ K, $T_\mathrm{c} \approx 0.99$ mK, $T_z \approx 11$ mK. At this time, we do not understand why our measured temperature appears higher than these predictions, but we have ruled out obvious effects, such as background gas collisions, laser frequency jitter, etc. We note, however, that if we conservatively estimate $r_\mathrm{m}(\max) = 15\ \mu$m, this gives $T_\mathrm{m}(\max) \approx 1$ mK. Therefore, the observed temperature would appear to be due to "hot" cyclotron motion. We also note that the predicted and experimental values of T_c/T_z approximately agree.

One serious shortcoming of the present apparatus [3,4] is that the net detection efficiency of the scattered light (fraction of scattered photons which are counted) is only about 10^{-5}, therefore limiting signal-to-noise ratio. A new apparatus with significantly improved detection efficiency is being constructed. This will improve signal-to-noise ratio in the double resonance experiments; moreover, it should allow simpler identification of a single ion because, over short time intervals, the fluorescence should maintain a steady value when the ion is in the $M_J = -1/2$ ground state and be totally absent when the ion is in the $M_J = +1/2$ ground state. We also note that when the Doppler width of the optical lines is less than the natural width, the *spectrum* of the scattered light is broadened only by the Doppler effect and not the natural width. If the laser linewidth is assumed negligible, the spectrum of the scattered light is composed of discrete lines, one at the laser frequency, and sidebands at $p\omega_z + q\omega_m + s\omega_c'$ where p, q, and s are positive and negative integers. For example, if we assume that only the cyclotron motion is excited and has a Maxwell–Boltzmann distribution in time, then the profile of these sidebands for light scattered in the backward direction is a gaussian with full width at half maximum $= 4(2 \ln 2 \cdot kT/M\lambda^2)^{1/2}$ where λ is the wavelength of the light (this is twice the normal Doppler broadening). The centroid is shifted from the laser frequency by $\Delta\omega = -4R/\hbar$ where $R = h^2/2M\lambda^2$. This spectrum could then give a more sensitive measure of the temperature [‡1].

‡1 The case of resolved sidebands in the Lamb–Dicke regime has been treated by Javanainen [8].

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