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Laser Cooling of Magnesium Ions: Preliminary Experimental Results

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Abstract. We describe a laser-cooling experiment on Mg^+ ions confined in an electromagnetic trap (Penning trap or rf trap) and give the preliminary experimental results. In particular, we have observed a laser cooling in the Penning trap configuration in which a measured temperature of about 1 K has been obtained.

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In the frequency-standard domain, stored ions transitions are good candidates for atomic clocks, but the main limitation of the accuracy and reproducibility is the high kinetic energy of the ions which produces a large 2nd order Doppler shift [1]. Laser cooling of these ions is consequently very attractive in order to obtain better accuracy and long-term stability [2]. Laser-cooling experiments have been performed at the NBS (Boulder) with Mg^+ [3] and Be^+ ions [4] in a Penning trap, at Seattle with Mg^+ ions in an rf trap [5] and at Heidelberg with Ba^+ ions in an rf trap [6]. The conditions in which these experiments have been performed are very different and it is consequently difficult to compare the results obtained for the two kinds of trap. In particular, it is important to be able to compare experimentally the cooling efficiency and the limit temperature obtained for the two traps. In the experiment reported here, Mg^+ ions can be confined in high vacuum by the static electric field and the static magnetic field of a Penning trap or by the alternative electric field of an rf trap, using the same experimental set-up.

This will give us the possibility to analyze and compare the cooling process in the two cases. In the Penning trap, the ions undergo harmonic motion along the magnetic field (axial motion) and a superposition of two circular motions (cyclotron and magnetron motions) in the plane perpendicular to the magnetic field. In the rf trap, they undergo a slow harmonic motion in the axial and radial directions superimposed to the micromotion at the frequency of the rf electric field.

Principle of the Experiment

Laser cooling occurs when the ions absorb photons whose frequency is slightly lower than an optical resonance frequency [7]. In our experiment, we use the $^2S_{1/2}-^2P_{3/2}$ transition of $^{24}Mg^+$ ions (wavelength: 280 nm). The temperature of the ions is deduced from the Doppler width of their absorption line, measured by recording the fluorescence light. The results reported here were obtained in the case of the Penning trap where cooling of both the magnetron and cyclotron modes can be accomplished by a single laser beam perpendicular to the trap axis [8].

Experimental Set-Up

The experimental set-up is described on Fig. 1. Characteristic dimensions [9] of the hyperbolic electrodes are $r_0=\sqrt{2}z_0=0.8$ cm. The material of the trap is Arcap AP4, chosen for its high quality in vacuum and amagnetic property.

In the Penning trap configuration, the magnetic field which is parallel to the axis of the trap is typically 0.74 T and the static voltage about 13 V.

In the Paul trap configuration, the rf drive frequency is 1.8 MHz, its amplitude about 200 V_{eff}. A

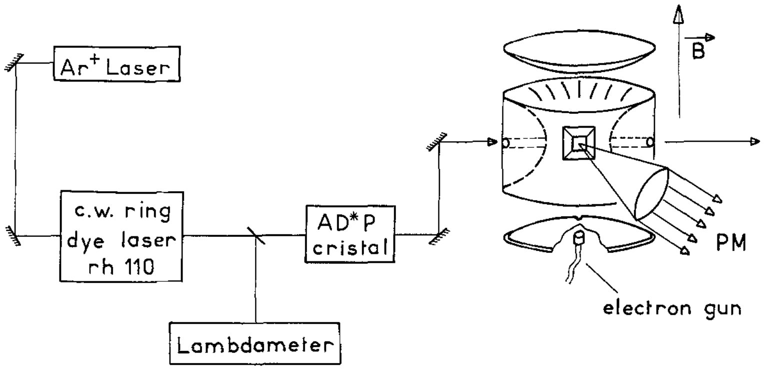

Fig. 1. Schematic of the experimental set-up

small static voltage (about 10 V) can be superimposed to optimize the confining parameters [10].

The cooling radiation passes through two slits of 16 mm height and 1.6 mm width tapped in the ring electrode. Mg vapor is produced by an oven and the ions are created in the trap by an electron beam coïncident with the trap axis and produced by a Philips-type thermocathode. The oven is a small thermocathode with a thin stainless steel tube fitted on it.

The trap is fixed on an OF HC copper support and housed in a stainless-steel-pyrex vacuum cell with three optical quartz windows which allow to introduce the cooling radiation and to detect the fluorescence light. Careful cleaning and vacuum baking of all internal components and of the cell allow to obtain a pressure below 10^{-7} Pa. An ion pump (25 l/s) maintains this vacuum.

The cooling radiation is derived from the frequency doubled output of a single mode, cw, Rhodamine 110 ring dye laser. This laser has an output power of approximately 300 mW at 560 nm when pumped by a 5 W Ar$^+$ laser. The dye laser frequency can be continuously swept on a range of 30 GHz and is doubled to produce the cooling radiation by a 90° temperature phase-matched AD*P (deuterated ammonia dihydrogen phosphate) crystal. This allows us to tune the radiation across the $^2S_{1/2}$, $M_J = \pm 1/2 \rightarrow {}^2P_{3/2}$, $M_J = \pm 3/2$ transitions in one sweep.

The uv output (up to 50 μW) is focused inside the trap and is polarized perpendicular to the trap/magnet axis. The beam waist diameter is about 100 μm. The beam is perpendicular to the axis of the trap: the temperature measured by the Doppler width of the absorption line is consequently due to the radial motion (magnetron and cyclotron motions in the case of the Penning trap).

The fluorescence light is observed through a hole tapped in the ring electrode, at right angle from the direction of the cooling beam. An optical device, made of four quartz lenses focuses the fluorescence photons on a solar blind photomultiplier, followed by a photon counting system.

The overall efficiency of the detection system is 10^{-3}. Scattered light is minimized by carefully diaphragming the Phe detected beam. The background counting rate due to scattered light and photomultiplier dark current is about 300 s^{-1} for 1 μW of incoming light. The vacuum cell is placed between the poles of an electro magnet which can produce a maximum field of 1.8 T. The vacuum pump and the photomultiplier are placed far enough (40 cm) from the electro-magnet in order to avoid magnetic perturbations. The wavelength of the laser is measured by a lambda meter [11] in reference with a He-Ne stabilized laser. The accuracy of the measurements is better than 10^{-7}.

Experimental Results

First of all, we measured before cooling the temperature of the ions, deduced from the Doppler width of the absorption line in the two configurations: the Paul trap and the Penning trap. It is to be noticed that in both cases, the temperature, of the order of 3 000 K, was much higher than the ambiant temperature. In the Paul trap, this can be easily explained by the rf heating [9] which transfers energy of the forced micro-motion into the secular motion via collisions with background gas. However, this phenomenon does not occur in the Penning trap. The heating may be caused by asymmetry-induced transport [12, 13]. The size of the ion cloud has been determined by sweeping the laser beam axially or in the equatorial plane of the trap and counting the number of fluorescence photons for each position. Typical axial dimension of the cloud was 1 200 μm and the magnetron radius was 1.5 mm, if we consider the half maximum of the fluorescence signal. Furthermore, the magnetron frequency can be determined by the Doppler shift observed when the beam is moved radially across the cloud (Fig. 2). The axial and

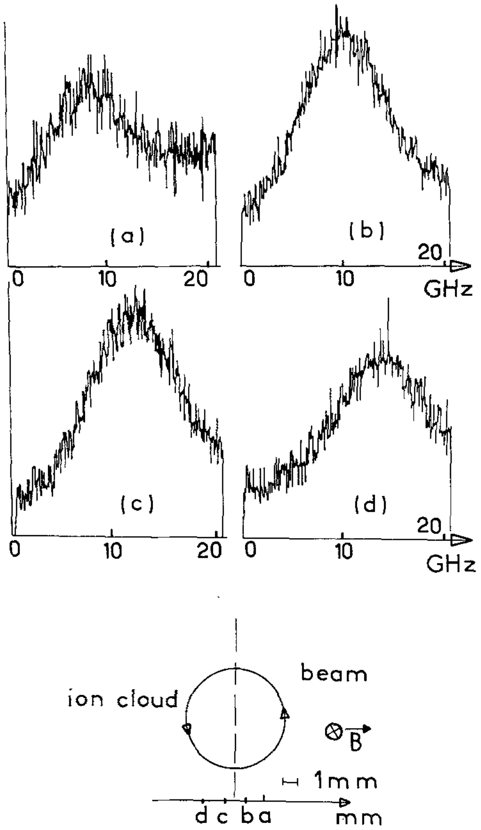

Fig. 2. Radial extension of the cloud. Magnetron frequency can be deduced from the Doppler shift of the line when the laser beam is moved

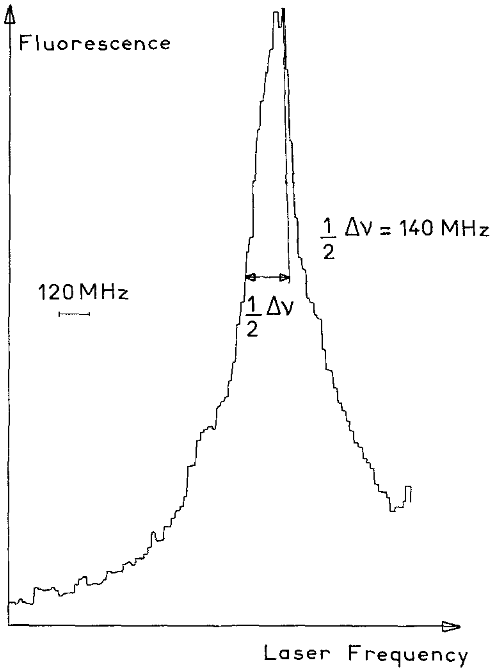

Fig. 3. Observed line when the ions are cooled. The asymmetry of the line is due to heating of the ions when the excitation frequency is larger than the resonance one

magnetron temperature deduced from these values are 1000 K and 850 K, respectively.

In a second step we observed cooling of the ions in the Penning trap configuration. In this case, the oven and electron gun must be off in order to increase the lifetime of the ions in the trap. The cooling radiation frequency must be lower than the ion resonance frequency. Since we have only one laser, the lineshape of the cooled ions was obtained by recording the fluorescence signal as this laser was swept in towards the resonance very slowly. Heating occurs when the laser frequency is above the rest frame resonance frequency and results in a spreading of the ion cloud and in strong decrease of the fluorescence signal, but an estimate of the temperature can be obtained from the lower half of the curve.

We obtained a linewidth of 280 MHz (Fig. 3) which corresponds to a cyclotron temperature of the order of 1 K if we take into account the natural linewidth of the line (43 MHz) and the contribution due to the size of the laser beam which interacts with ions of different magnetron velocities giving rise to a spread in frequency of the order of 130 MHz.

In an other experiment where the linewidth was 600 MHz ($T \lesssim 20$ K) we have measured an axial extension of the ions of 125 μm which corresponds to an axial temperature of 30 K.

Conclusion

We have built an apparatus which allows to confine ions in a Penning and in an rf trap using the same electrodes in order to compare the laser cooling in both cases. The apparatus has been successfully tested and a strong cooling observed in the Penning trap configuration. It will be used to study the effect of various parameters (ion number, confining parameters, neutral gas pressure, ...) on the cooling efficiency in both configurations.

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