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Investigations of a two-level atom in a magneto-optical trap using magnesium

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Abstract

Magnesium atoms are cooled in a magneto-optical trap (MOT) using the $3s^2\ ^1S_0 \rightarrow 3s3p\ ^1P_1$ resonance transition. Magnesium is a simple atom which offers a unique possibility for comparison to the Doppler theory of laser cooling. We measure trap parameters as a function of laser-intensity, -detuning and magnetic field gradient. We find the main features well accounted for by Doppler theory, but temperature measurements gave significant higher values than predicted by the Doppler theory. We also observe radiation pressure effects within the MOT that limit the maximum achievable density. Comparing our results to predictions by models in the literature shows a good agreement. Recently we have improved our set-up and now trap about 150×10^6 atoms.

Keywords: two-electron atoms, two-level atom, cold atoms, laser cooling, Doppler cooling theory, magneto-optical trap, multiple-phonon scattering

1. Introduction

Over the past years laser cooling of alkaline-earth atoms has progressed significantly. The main effort has concentrated on the cooling of magnesium, calcium and strontium atoms [1–10], while beryllium and barium have not yet been trapped. Alkaline-earth systems have a number of interesting features. They are effectively two-electron atoms with a simple internal structure, often free of fine and hyperfine interaction. Thus, these atoms offer an excellent benchmark system for the testing of, for example, laser cooling theories [11, 12] and quantum mechanical many-body theories [13]. In addition, alkaline-earth atoms have an ultra-narrow intercombination line suitable for optical frequency standards [2, 6, 14, 15]. However, these systems present serious experimental challenges since their resonance wavelengths are typically in the UV range, inaccessible to standard photon sources. Because the $^1S_0$ ground state of alkaline-earth atoms is non-degenerate, sub-Doppler cooling is not possible on the resonance transition and the temperature is often limited to a few millikelvin. However, new cooling techniques based on the intercombination line have been suggested and recently demonstrated for calcium [6]. For strontium sub-Doppler cooling for isotopes with hyperfine structure has been realized in a single stage cooling scheme [7].

In the pioneering work of the Hannover group [1] magnesium was trapped for the first time using the resonance transition. In a series of impressive papers the group explored atom interferometry using the 457 nm intercombination line $3s^2\ ^1S_0 \rightarrow 3s3p\ ^3P_1$, both in a magneto-optical trap (MOT) and in an atomic beam, see [2] for a recent account. In this paper we present new results for magnesium atoms cooled on the $3s^2\ ^1S_0 \rightarrow 3s3p\ ^1P_1$ resonance transition in a MOT. Magnesium has an additional advantage compared to the other alkaline-earth atoms studied since no lower lying D-states are present in the cooling scheme. The magnesium atom is accordingly very close to an ideal two-level atom. Laser cooling of a single two-level atom is well understood, but less is known about many-atom effects, where light pressure forces and atom dynamics become important. This paper reports the MOT parameters such as the number of atoms, radius and temperature of the atom cloud as a function of laser intensity,

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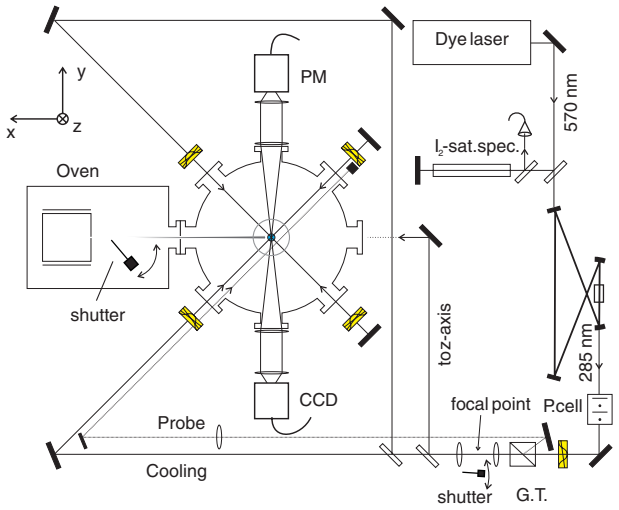

Figure 1. Schematic top view of the experimental set-up. In the MOT chamber atoms are captured directly from the thermal beam produced in the oven chamber. For MOT diagnostics we use a CCD camera and a photomultiplier. The z-axis indicated on the figure corresponds to the symmetry axis of the two magnet coils.

(This figure is in colour only in the electronic version)

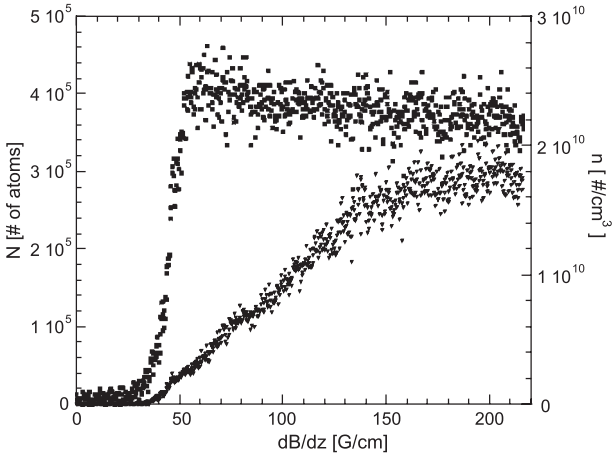

Figure 2. Number of captured atoms N(■) and mean atom density n(▼) as a function of magnetic field gradient in the z-direction. The laser detuning is $\delta = -55$ MHz and the total saturation parameter $S_0 = 6$.

detuning and magnetic field gradient. Experimental findings are compared to standard Doppler theory for a two-level atom.

2. Experimental set-up

A schematic diagram of the experimental set-up is given in figure 1. Light (570 nm) from a coherent 899-21 single mode dye laser is frequency doubled in an external four mirror cavity using BBO. At input powers of 600 mW, we routinely generate 30 mW at 285.2 nm [3]. The absolute laser frequency is referenced to a set-up monitoring iodine hyperfine transitions through saturated absorption of the 570.4 nm beam [4].

The MOT beams are all about 1 mm in diameter, which is sufficient for magneto-optical trapping of magnesium. The total laser power for MOT operation is controlled using a $\lambda/2$-plate followed by a Glan–Thompson (GT) prism. Two beam splitters divide the initial beam into equal intensity components for MOT operation. Typically we have a power of 5–6 mW in each MOT beam, corresponding to a total saturation parameter (all six laser beams) of about $S_0 = 6I/I_0 = 6$. With a 2 ns lifetime for the $^1P_1$ excited state, intensities as large as $I_0 = 446$ mW cm^{-2} are required to saturate the main cooling transition. This provides, however, a very efficient deceleration $a_{\max} \sim 15 \times 10^6 g$, allowing us to load a MOT from a thermal beam without the use of a Zeeman slower. The MOT is a standard type with two small coils of 25 mm diameter and 20 mm separation. Our coil assembly can deliver a gradient up to 220 G cm^{-1} (in the z-direction) needed for experiments. When the oven operates at 425 °C we capture up to 10^6 atoms. The corresponding FWHM size of the MOT is about 400 μm. Optimal trapping was found for relatively large laser detunings, of about -100 MHz, where the capture velocity is large. Nevertheless, a MOT exists in a frequency range of -15 to -130 MHz.

The number of captured atoms is limited by near resonant photo-ionization from the 3s3p $^1P_1$ state [3]. This results in a typical lifetime of 0.3 s measured by monitoring the fluorescence of the MOT as a function of time, after the load beam is cut off by the shutter indicated in figure 1.

Atom fluorescence is recorded by a photomultiplier and we use a standard CCD camera, where the chip window is removed, for spatial monitoring of the MOT. For measurements of the MOT characteristics we simultaneously record a 800-picture CCD movie and monitor the fluorescence, while ramping the magnetic field gradient or the laser detuning. For each picture we perform a Gaussian fit yielding the MOT radius in the x- (low gradient) and z-direction (high gradient). The MOT radii, magnetic field gradient, laser detuning and laser intensity are stored for later analysis.

The MOT temperature is measured by a standard time-of-flight technique, using a probe beam located about 10 mm below the MOT. A mechanical shutter switches off the MOT light in less than 50 μs and a Pockels cell subsequently switches the MOT light polarization to generate an intense probe beam though reflection on the GT prism. Our set-up can also trap the two other stable magnesium isotopes ^{25}Mg (10%) and ^{26}Mg (11%) independently, but here we only report on measurements with ^{24}Mg (79%). Typically the pressure in the oven chamber is 10^{-8} mbar and 4×10^{-10} mbar in the MOT chamber.

3. Experimental results and discussion

3.1. Measurements scanning the magnetic field gradient

Studies of the MOT radius as a function of magnetic field gradient show directly the influence of radiation pressure effects in the MOT, an effect first observed in alkali atoms [15–19]. We compare our results for magnesium to predictions of a two-level model developed by Sesko *et al* [17].

Figure 2 displays the number of trapped atoms and the corresponding mean atom density as a function of the magnetic field gradient. The laser detuning is $\delta = -55$ MHz and total saturation parameter $S_0 = 6$. The number of atoms quickly reaches a fairly constant value. We attribute the slight decrease to the reduction of capture velocities with the increased magnetic field gradient since the stopping

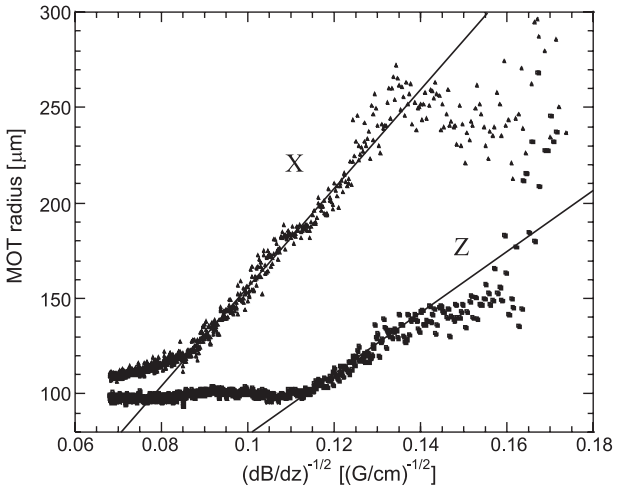

Figure 3. The x (▲) and z (■) MOT radii as functions of the inverse square root of the magnetic field gradient for $\delta = -55$ MHz and total saturation parameter $S_0 = 6$. The straight lines correspond to a non-interacting classical gas obeying the equipartition theorem.

length is slightly reduced. The density gradually increases to 1.8×10^{10} atoms cm^{-3} at which it levels off. As the magnetic field gradient rises the atom cloud becomes more and more compressed, thus increasing the density. For a trapped classical gas of independent atoms the cloud size is limited by the temperature T (equipartition relation):

$$\tfrac{1}{2}\kappa_{ii}\langle r_i^2\rangle = \tfrac{1}{2}k_{\mathrm{B}}T, \tag{1}$$

where κ_{ii} is the spring constant, r_i the radius for $i = (x, y, z)$ and k_{B} Boltzmann's constant. Replacing the spring constant and the temperature with the expressions from Doppler theory [12] the MOT radius can be expressed as

$$\langle r_i^2\rangle = \left(\frac{\hbar\Gamma^3}{2^5 k\mu_{\mathrm{B}}}\right)\frac{(1 + 2N(I/I_0) + (2\delta/\Gamma)^2)^3}{2N(I/I_0)\delta^2}(\partial B/\partial r_i)^{-1} \tag{2}$$

where $\frac{\partial B}{\partial r_i}$ is the magnetic field gradient along $i = (x, y, z)$, δ is the laser detuning, k the wavevector, $\Gamma/2\pi = 79$ MHz the natural line width, I/I_0 single beam saturation parameter, I the single beam intensity and N the number of dimensions: here $N = 3$ is anticipated. Thus we expect the density to scale as $(\partial B/\partial r_i)^{(3/2)}$ for a classical gas, if the temperature and atom number is assumed to be independent of magnetic field gradient, as verified experimentally. We did not find any significant temperature dependence of the magnetic field gradient in our range; see discussion later in this section.

Figure 3 shows the MOT (x, z) radii as functions of the inverse square root of the magnetic field gradient in the z direction (x-radius = y-radius = $\sqrt{2}z$-radius in order to satisfy Maxwell's equation $\vec{\nabla}\cdot\vec{B} = 0$).

A gas following equation (1) will display a linear relationship in figure 3 if the temperature and atom number is independent of the magnetic field gradient. The magnesium gas clearly behaves as a non-interacting gas until 0.115 G$^{-1/2}$ cm$^{1/2}$ for the z-component or 0.085 G$^{-1/2}$ cm$^{1/2}$ for the x-component. Below these values it is not possible to compress the cloud any further. Here the atoms start to interact through reabsorption of scattered photons within the atom cloud, and finally the gas cannot be compressed any further. This provides a direct observation of the so-called multiple scattering regime [20], where reabsorption of fluorescence photons emitted from nearby atoms gives rise to a net repulsive force. This effect sets in for the z-direction at lower magnetic fields compared to the x-direction, since the mean free path of a scattered or a fluorescence photon is smaller for the z-direction. For a two-level atom the scattering/reabsorption effect can be modelled accurately. As shown in [14–16] it is possible to derive a critical density n_{c} where the repulsive force becomes significant:

$$n_{\mathrm{c}} = \frac{3\kappa c}{I_{\mathrm{tot}}\sigma_{\mathrm{L}}^2(\sigma_{\mathrm{R}}/\sigma_{\mathrm{L}} - 1)}. \tag{3}$$

Here σ_{L} denotes the optical cross section for absorbing photons from the laser field and σ_{R} is the optical cross section for absorbing rescattered photons. The spring constant κ is calculated using the Doppler theory for laser cooling. In general $\sigma_{\mathrm{R}} \neq \sigma_{\mathrm{L}}$ since reradiated light in general has a different spectral distribution compared to the absorbed laser light. The reradiated light has two spectral contributions: elastic Rayleigh scattering at the laser frequency and inelastic scattering described by the Mollow triplet [21]. Thus, we should not be able to produce densities significantly higher than n_{c}.

The cross section for absorbing photons from the laser field σ_{L} is given by

$$\sigma_{\mathrm{L}} = \left(\frac{3\lambda^2}{2\pi}\right)\frac{1}{1 + (I_{\mathrm{tot}}/I_0) + (2\delta/\Gamma)^2} \tag{4}$$

where $\lambda = 285.2$ nm and $I_{\mathrm{tot}} = 6I$. For our experimental conditions of $\delta = -55$ MHz and a total saturation parameter of about $S_0 = 6$ the fraction of elastically scattered light amounts to 1/3 of the total amount of scattered photons. In order to calculate the critical density we numerically computed the ratio $\sigma_{\mathrm{R}}/\sigma_{\mathrm{L}}$ in a way similar to that described in [17]. We obtained a value of $\sigma_{\mathrm{R}}/\sigma_{\mathrm{L}} = 1.63$. Using instead the approximate expression developed in [18] we derived a smaller value of $\sigma_{\mathrm{R}}/\sigma_{\mathrm{L}} = 1.19$. However, the formula in [18] is not directly applicable to our parameter range. Finally, we obtained a critical density of about $n_{\mathrm{c}} \simeq 1.5 \times 10^{10}$ atoms cm^{-3} in good agreement with our measured maximum value of the mean density of $n_{\max} \simeq (1.8 \pm 0.5) \times 10^{10}$ atoms cm^{-3}, see figure 2. The estimated uncertainty is about 30%, mainly due to the absolute calibration of our photomultiplier (where a NIST calibrated power meter was used). We did not include effects from the magnetic field, the spatial extension of density distribution, optical pumping effects etc so only an approximate agreement is expected. No deviation from a Gaussian distribution was observed, not even in the multiple scattering regime where one would expect a flattening in the density profile. A similar trend has also been observed for alkali atoms where only larger densities gave rise to a non-Gaussian density profile [10, 20].

3.2. Scanning the laser detuning

In a series of measurements we investigated the MOT size as a function of laser detuning. Figure 4 displays the MOT x-radius as a function of laser detuning for $S_0 = 6$. The

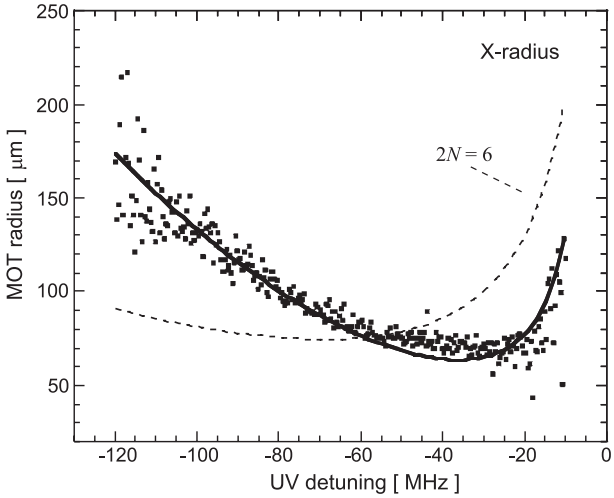

Figure 4. MOT x-radius (■) as function laser detuning for $S_0 = 6$ and $(\partial B/\partial x) = 80$ G cm^{-1}. The solid curve is a fit to based on equation (2) for a two-level atom. The effective saturation coefficient $2N_0 = 0.6$ and a scaling $c = 2.1$ on the radius. For comparison we show a fit, dashed curve, where $2N$ is fixed to 6 and $c = 1$.

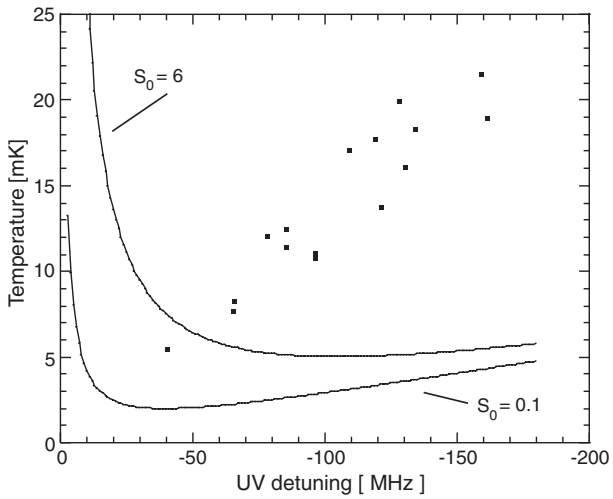

Figure 5. The MOT temperature (■) measured as a function of laser detuning, with $S_0 = 6$ and $(\partial B/\partial z) = 160$ G cm^{-1}. The solid curves are the prediction of Doppler theory with saturation parameters of $S_0 = 0.1$ and 6.

measurement was carried out with a magnetic field z-gradient of 160 G cm^{-1}. For this gradient the z-radius showed no significant change since the multiple scattering dominated. This was not the case for the x-direction. As the laser frequency approaches resonance, the MOT radius is reduced until a value of -20 MHz where the radius increases again, probably due to an increase in the MOT temperature. In a small range at around -40 MHz the radius levels off as a consequence of the multiple scattering. At larger detunings the density is too low to reach the multiple scattering regime, and for detunings very close to resonance temperature effects lower the density below n_c. The factor of $2N$ is often discussed [12, 22, 23] and represents a mere approximation to the real 3D situation only. The dashed curve represents a fit in the ideal case where $2N = 6$. The solid curve is a fit based on equation (2) for a two-level atom, where the multiple beam saturation coefficient $2N$ and a scaling coefficient c on the radius were used as fit parameters. The scaling coefficient is defined as r (measured) $= cr$ (theoretical).

Our experiments gave the value $2N = 0.6 \pm 0.1$ independent of the power used ($3.6 < S_0 < 18$). We found the theoretical radius must be scaled up by a factor of $c = 2.1$ in order to fit whereas 1.0 is expected by equation (2). The differences we attribute to the presence of multiple scattering which will increase the radius. However, no theory is available describing Doppler theory in the presence of multiple scattering, which is the case for some of our detunings.

3.3. Temperature measurements

Temperature measurements performed at different magnetic field gradients reproduced predicted results to within 30%. Figure 5 presents temperature measurements as a function of laser detuning.

We observe a temperature which is a factor of 4 or 5 higher than predicted by Doppler theory. The higher temperature is consistent with our measurements of the MOT radius, which gave a factor 2 larger than predicted by the Doppler theory. The temperature is thus expected to be a factor of 4 higher. However, the observed temperature increases linearly for large laser detunings, as expected.

Similar results were observed in other two-electron systems. Measurements on calcium and strontium MOTs [5, 11] also yielded temperatures significantly higher than the Doppler predictions. In [11] the authors concluded that the damping coefficient and spring constant were well accounted for by Doppler theory. But their temperature measured as a function of the trapping beam intensity was much higher than predicted by Doppler theory. This suggests that the scattering rate is not well described by Doppler theory.

Our data support this conclusion. The measurements of the radius as function of detuning agrees very well with Doppler theory, but the prefactor, which essentially scales the temperature, and the factor $2N$ is significantly different from 6. We thus conclude that the functional dependence of Doppler theory is correct, but the scaling of the temperature is wrong. However, additional heating mechanisms in the form of, for example, standing wave effects, rescattering of fluorescence photons (from the Mollow triplet) at zero or positive detuning are not described by standard Doppler cooling theory.

3.4. Dependence on laser beam diameter: increasing the number of trapped atoms

Recently, we expanded the laser beams from 1 mm to a diameter of about 8 mm. In this configuration we were able to trap more than 150×10^6 atoms with mean densities of $n \sim 1 \times 10^{11}$ atoms cm^{-3} and with a trap lifetime of 7 s (see figure 6). At these densities the MOT form is dominated by rescattering of photons and has a spherical form of radius 0.7 mm. The higher number of trapped atoms and longer lifetime are explained by a combination of reduced photo-ionization losses and a bigger capture volume. Analysis shows that in this laser intensity regime our MOT lifetime is limited by the background pressure in our MOT chamber and not by near resonant photo-ionization.

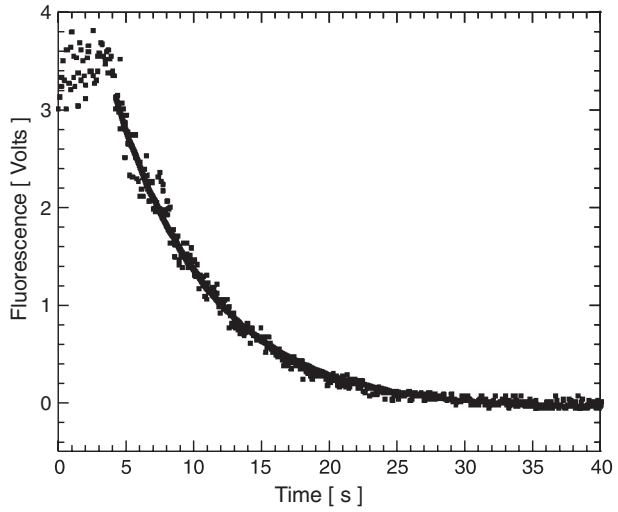

Figure 6. Decay of the MOT (■) as a function of time. The data are obtained by expanding the laser beam about eight times. The solid curve is an exponential fit to the data giving a lifetime of 7 s.

4. Summary

This paper presents MOT size, density and temperature measurements for magnesium laser cooled using the 285 nm $3s^2\ ^1S_0 \rightarrow 3s3p\ ^1P_1$ resonance transition. This is an ideal two-level atom which allows the testing of simple laser cooling theories. We verified that MOT size scales as predicted by Doppler theory, but a scale factor of $c = 2.1$ on the radius was introduced to match the absolute value. This is in agreement with our temperature measurements which are a factor of 4–5 higher than predicted by Doppler theory. This suggests additional heating mechanisms, as also observed in other alkaline-earth systems. We obtained a direct observation of the multiple scattering regime for our MOT. Measurements of the corresponding critical density were in good agreement with the previously developed two-level model calculations of Walker *et al*. By increasing the laser diameter of our trapping beams by a factor of 8 we are able to increase the number of captured atoms from a few 10^6 atoms to 150×10^6 atoms.

Acknowledgments

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