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Optical Trapping in a Cesium Cell with Linearly Polarized Light and at Zero Magnetic Field.

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Abstract. – We have found that linearly polarized light can be used efficiently for optical trapping of cesium atoms in a magnetic-quadrupole field. The number and density of atoms of the trapped samples are comparable to a standard magneto-optical trap with σ^+-σ^- polarized light, but the influence of the magnetic-quadrupole strength is strikingly different. When the polarization of counterpropagating light beams is orthogonal, trapping is observed also for zero magnetic field.

The preparation of very cold samples of neutral atoms has become commonplace through the invention of magnetically assisted radiation pressure cooling with circularly polarized light in a magnetic-quadrupole field, or shorter magneto-optical trap (σ^+-σ^- MOT) [1]. A case in point was the successful demonstration of magneto-optical trapping directly from the gas phase [2, 3]. This experimental method has simplified a whole series of new physical systems including, for instance, the observation of atoms localized in potential wells of an optical lattice at a subwavelength scale [4, 5].

The capture mechanism in a magneto-optical trap is conceptually different from the storage mechanism and largely dominated by Doppler cooling as investigated by Gibble *et al.* [6] and Lindquist *et al.* [7]. According to these experiments, the magnetic modification of the radiation pressure force through Zeeman detuning does not play a very significant role in the capture process other than defining a centre for the binding force, provided the magnetic-field gradient does not exceed several G/cm.

This interpretation is most suitable for the widespread σ^+-σ^- configuration in which three orthogonal pairs of counterpropagating σ^+-σ^- polarized laser beams intersect at the centre of the quadrupole field.

A new magneto-optical trap with a linear polarization configuration was reported by Emile *et al.* [8]. In contrast to the σ^+-σ^- MOT, stimulated magneto-optical forces [9] may help to increase the trapping efficiency in such a trap.

We have examined the dependence of the magneto-optical trap on different linear polarization geometries. Using the non-orthogonal configuration of fig. 1*a*) and varying the polarization angle between incident and retroreflected beams synchronously in all three arms, we observe a continuous class of magneto-optical traps which is most intense and stable when the angle is 90° (the lin-$\perp$-lin configuration). A similar observation was also communicated to us by Sidorov [10].

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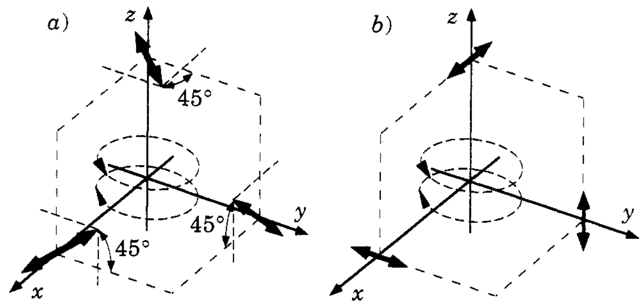

Fig. 1. – Polarization directions of incoming laser beams for magneto-optical trapping with linearly polarized light: *a*) non-orthogonal geometry; *b*) orthogonal geometry. Circles indicate the quadrupole coils and current direction.

In a σ^+-σ^- MOT typically several 10^7 atoms as reported numerous times are stopped at random positions in the capture volume. With the aid of the magnetic field they are subsequently collected in a volume much smaller than the beam diameter. A similar number of cold atoms should be found in the corresponding and field-free σ^+-σ^- molasses filling the capture volume. Hence we expect the density and consequently the fluorescence intensity because of the larger volume to be at least two orders of magnitude lower than at the centre of a σ^+-σ^- MOT. This density is much harder to detect, which explains why little has been reported about molasses captured directly from the gas phase except in the work of the Paris laser cooling group [11-13], and why experimental data for σ^+-σ^- MOTs do usually not start below a minimum field gradient of order 1 G/cm.

In our apparatus we observe loading of optical molasses from the gas phase as predicted when no magnetic field is applied. It covers most of the intersection volume irradiated by all six laser beams, roughly reflecting their intensity distribution. Surprisingly, however, a small bright cloud of atoms of diameter 1.8 mm (FWHM) very much resembling regular magneto-optical trapping and much narrower than the laser beams is observed in the non-orthogonal lin-$\perp$-lin configuration at zero magnetic-field gradient. The bright spot is furthermore observed well into the regime with reversed field gradient. This observation is no longer consistent with optical molasses and implies the existence of a central trapping force not related to a magnetic field.

Since we do not observe lin-$\perp$-lin trapping nor zero-field trapping in a compact gas cell at some 10^{-8} mbar, we have concluded that both good vacuum conditions and, even more importantly, trapping laser beams with a reasonable diameter of order 10 mm are essential for a successful observation of the trapping phenomena reported here. The cell is a stainless-steel chamber and a residual background pressure in the 10^{-10} mbar pressure range is accomplished with a strong ion pump and a graphite foil for gettering excess cesium. A small reservoir can be cooled or heated to adjust cesium partial pressure. Laser beams having a $1/e^2$ diameter of 10 mm are derived from a Ti-sapphire laser with single-mode output power of about 1 W. They are spatially filtered through a single-mode fibre and used as trapping light driving the $F = 4 \rightarrow F' = 5$ hyperfine transition of the cesium D_2 line. For repumping a diode laser is tuned to the $F = 3 \rightarrow F' = 4$ transition and superposed with two of the trapping laser beams. We have typically operated our trap at a detuning $\delta/\gamma = -2$, where γ is the natural linewidth ($\gamma = 5.3$ MHz). The saturation parameter at the centre of each incident laser beam can be varied from $s_0 = I/I_0 = 0$–120, where $I_0 = 1.1\ \mathrm{mW/cm^2}$ is the saturation intensity.

For proper alignment and overlap of laser beams with the magnetic-quadrupole field, we observe and record a slow-scan CCD image of the trapping region, first at zero quadrupole field and then at a gradient of 12 G/cm, the maximum possible value in our set-up. The quadrupole field causes a spatial Zeeman modulation of the fluorescence and allows simple *in situ* location of the magnetic zero point in the difference image for precise alignment of the six laser beams.

Our set-up consists of 3 independently adjustable laser beams retroreflected with a mirror and orthogonal to each other to better than 1°. We have usually employed the non-orthogonal polarization configuration of fig. 1*a*), which has incident beams linearly polarized and inclined at 45° relatively to the coordinate axes. A quarterwave plate before the retroreflecting mirror allows to vary the polarization angle continuously between counter-propagating beams from lin-‖-lin (0°) via lin-45°-lin to lin-⊥-lin (90°). Insertion of another quarterwave plate before the vacuum vessel converts the arrangement to the σ^+-σ^- MOT without any other realignment. The number of trapped atoms is calculated from the fluorescence image as recorded by the calibrated CCD camera.

At a field gradient of 8 G/cm, we observe a very bright σ^+-σ^- MOT with $2 \cdot 10^7$ atoms at an average density of $5 \cdot 10^{10}$ cm^{-3} in the radiation trapping limit [14, 15]. It is loaded with a time constant $\tau = 0.8$ s from the background gas at room temperature. In the upper row of fig. 2 a cross-section of the σ^+-σ^- MOT fluorescence distribution is shown.

While the σ^+-σ^- MOT shows a very robust constitution, we find all other configurations to be sensitive to even small variations of the alignment. With the lin-45°-lin geometry we reproduce the trap reported by Emile *et al.* [8] who find a decrease in atom number when the polarization angle is varied in one arm only. However, in an extension to this work we observe even more intense trapping signals if each pair of incoming and retroreflected beams has a polarization angle of 90° (lin-⊥-lin). Magneto-optical trapping is still observed if the polarizations are parallel (lin-‖-lin), although the number of atoms is now only 1/3 of the maximum at lin-⊥-lin. The loading time constant of order 2.5 s greatly exceeds the corresponding time constant in the σ^+-σ^- MOT under the same pressure conditions. To our knowledge no explanation is known for this difference which has also been noted in the corresponding molasses experiments [11]. In the upper row in fig. 2 we show fluorescence cross-sections of selected linear trap configurations in comparison with the σ^+-σ^- MOT. The total number of atoms in the lin-⊥-lin trap is two times smaller than in the σ^+-σ^- MOT and the density about ten times smaller since it also has a larger diameter.

The difference between the σ^+-σ^- MOT and the lin-⊥-lin trap is most apparent when the number and density of trapped atoms is measured as a function of the quadrupole gradient

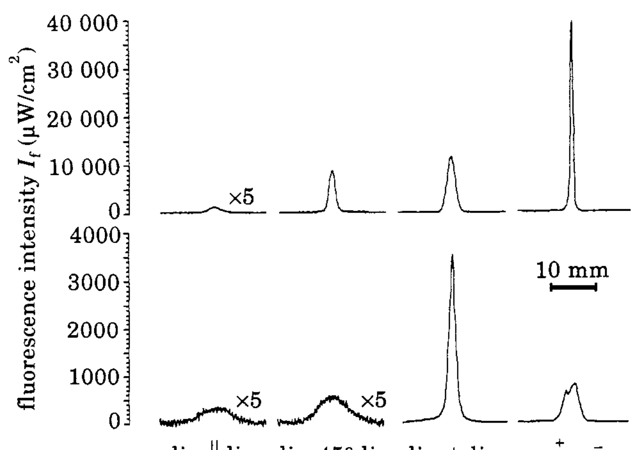

Fig. 2. – Optical trapping of cesium atoms: cross-sections of the fluorescence image of the 10 mm diameter trapping volume. Upper row: magneto-optical trapping at $\partial B/\partial z = 8$ G/cm. Lower row: optical trapping at zero magnetic field.

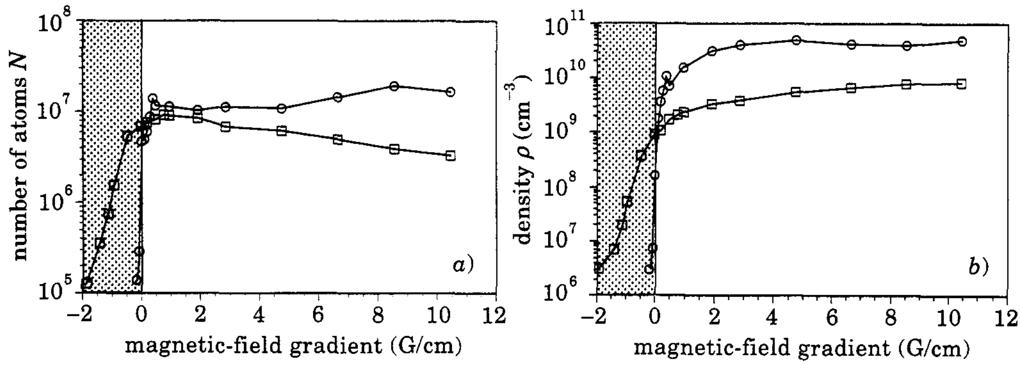

Fig. 3. – Magnetic-field dependence of *a*) the equilibrium number N of atoms and *b*) the average density ρ in the σ^+-σ^- MOT (○) and the lin-⊥-lin trap (□) at $\delta = -2\gamma$, $s_0 = 140$. The shaded area is the region of negative-field gradient (reversed quadrupole). Statistical uncertainty for number and density of atoms is smaller than 5%, global uncertainty is about 40%.

(fig. 3*a*), *b*)). In the σ^+-σ^- MOT both quantities show a weak dependence for $\partial B/\partial z > 2$ G/cm. Below 0.5 G/cm a very steep drop in total fluorescence intensity is observed and accompanied by an expansion of the cloud from 0.6 mm diameter (FWHM) at higher fields to 3 mm at zero field. At zero field a fluorescence covering most of the irradiated volume is an indication of atoms stopped at random positions and slowly diffusing out of optical molasses. The number of atoms in the σ^+-σ^- molasses is about 1/4 of the 8 G/cm σ^+-σ^- MOT. No molasses was observed below -0.8 G/cm.

In the lin-⊥-lin trap the number of atoms slowly increases to a maximum near 1 G/cm when the gradient is lowered. In contrast to the σ^+-σ^- MOT, only a small decrease is observed towards zero field. Instead, the lin-⊥-lin trap extends steadily into the region of reversed quadrupole sign though at much reduced numbers of trapped atoms. With a higher integration constant of the CCD camera, trapping of atoms could be observed until -12 G/cm. For the lin-45°-lin as well as for the lin-‖-lin geometry, we again observe molasses captured from background gas but no «zero-field trapping» as for the lin-⊥-lin case (fig. 2, lower row).

While the steep transition fort the σ^+-σ^- MOT already indicates that residual magnetization does not play a significant role for the observation of zero-field trapping, we have performed the following additional tests: for zero current in the quadrupole coils, residual field gradients were measured below 0.03 G/cm. Trapping was also observed in homogeneous magnetic fields up to 2 G in all directions, excluding any spurious zero point of magnetic field within the irradiated volume.

Experimentally we find that the lin-⊥-lin zero-field trap is most intense if the counter-propagating beams in each arm are slightly misaligned forming an angle of 0.5°–1°. This situation is much reminiscent of the observation which was called «supermolasses» by Chu *et al.* [16]. In order to reproduce this experiment, we have also employed the lin-⊥-lin polarization geometry of fig. 1*b*). In contrast to fig. 1*a*), all incident light beams have mutually orthogonal polarizations now. In this situation we obtain only very weak magneto-optical trapping. At zero field and perfectly aligned beams, optical molasses is observed. A larger misalignment of about 2° is necessary to produce an intense fluorescent cloud in this case. This situation seems to be equivalent to sodium supermolasses.

We have performed comparative temperature measurements of the σ^+-σ^- MOT and the magnetic lin-⊥-lin trap using the method of forced position oscillation by superposing a small sinusoidally varying homogeneous magnetic field. From the mechanical response of the trapped sample of atoms, both the spring constant κ and the friction coefficient can be

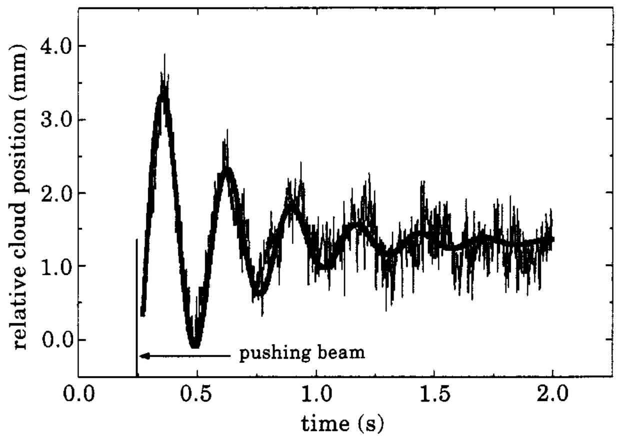

Fig. 4. – Position measurement of the trapped atomic sample at zero magnetic field. A 10 ms long resonant pushing beam is applied to generate an initial displacement. Detuning of the trapping light beams $\delta = -3\gamma$, saturation parameter $s_0 = 80$.

determined [17, 18]. The spring constant is $\kappa = m_{\mathrm{Cs}}\omega_0^2$, where ω_0 is the frequency at which the position oscillation follows the driving field with 90° phase lag. At 8 G/cm ($\delta/\gamma = -3$, $s_0 = 80$) we measure $\kappa_\sigma = 7\cdot 10^{-21}$ kg/s^2 for the σ^+-σ^- MOT and $\kappa_\perp = 5\cdot 10^{-22}$ kg/s^2 for the lin-$\perp$-lin trap, corresponding to $\omega_0/2\pi = 29$ Hz and 8 Hz, respectively. The spring constants decrease when the magnetic-field gradient is lowered as observed by Wallace *et al.* [19].

The temperature then can be inferred from a knowledge of the spatial extent of the cloud by means of the equipartition theorem. We consistently find temperatures around 20 μK for the magnetic lin-$\perp$-lin trap and 100 μK for the σ^+-σ^- MOT under the same experimental conditions, which is well below the Cs-Doppler limit of 125 μK. It has been established [20] that near the zero point of the quadrupole field sub-Doppler temperatures very much resembling corresponding molasses conditions exist in a σ^+-σ^- MOT. Clairon *et al.* [11] have generally measured lower temperatures for lin-$\perp$-lin molasses. Our measurements confirm this observation also for magneto-optically trapped atoms.

At zero field we cannot displace the fluorescing cloud by homogeneous magnetic fields. A pulsed pushing beam, however, causes the sample to oscillate while relaxing to its former position. From a recording with a position-sensitive detector (fig. 4) both the spring constant and the damping constant can be evaluated. For $\delta/\gamma = -3$, $s_0 = 80$, we find $\kappa = 1.4\cdot 10^{-22}$ kg/s^2.

Without magnetic-quadrupole field a centre is still defined by the maximum of the trapping light intensity distribution. The intensity variation causes a spatial dependence of the average saturation parameter $\langle s_0\rangle = \bar{s}_0 \exp[-2(r/r_0)^2]$, where the beam waist has $r_0 = 5$ mm.

Since we do not control the relative phases of the counterpropagating light beams, we neglect the influence of optical lattices at the microscopic wavelength scale which may exist for time scales short compared to acoustic vibrations. Instead we assume that atomic motion is governed by the dipole force averaged over the wavelength scale and hence reflecting the intensity envelope gradient. Neglecting atomic orientation, we can calculate an upper limit for the one-dimensional dipole spring constant from the averaged optical potential

$$U_{\mathrm{dip}} = \hbar\delta \ln\{1 + \langle s_0\rangle(\gamma/2)^2/[\delta^2 + (\gamma/2)^2]\},$$

[21] yielding $\kappa = \partial^2 U_{\mathrm{dip}}/\partial r^2|_{r=0}\, 1.1\cdot 10^{-21}$ kg/s^2 ($\delta/\gamma = -3$, $\bar{s}_0 \approx 80$ for a single beam). This result shows that dipole forces could play a significant role in the binding mechanism. In the shallow potential corresponding to the measured spring constant the temperature of stored atoms

cannot exceed 80 μK which is below the temperature measured for the σ^+-σ^-–configuration and could explain why no zero-field trapping occurs in this polarization geometry. Optical trapping by dipole forces has been observed earlier by Chu *et al.* [22] and also by Miller *et al.* [23].

Linearly polarized light can be used efficiently for trapping of atoms at sub-Doppler temperatures. The lin-⊥-lin polarization geometry is particularly suitable to prepare a sample of slow atoms with considerable density without the help of a magnetic field but in the convenient overall geometry of a regular σ^+-σ^- MOT. We have discussed the average dipole force derived from the intensity gradient of the intersecting laser fields as a candidate for a binding force in the absence of magnetic fields. The elimination of magnetic fields may be of interest for atomic fountain applications like atomic clocks [24] for which residual magnetic fields have been identified as a major source of systematic errors.

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