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Neutral Cesium Atoms in Strong Magnetic-Quadrupole Fields at Sub-Doppler Temperatures.

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Abstract. – We have investigated optical capture of neutral cesium atoms by radiation pressure forces in a stiff magnetic-quadrupole field. Permanent magnets were used to generate field gradients ranging from 60 G/cm to more than 300 G/cm. With increasing gradient we observe a step decrease in the equilibrium number of trapped atoms but only a moderate reduction of their density. From the dynamics of the trapped atomic sample we derive temperatures as low as 40 μK or 30% of the Doppler limit even in these strong magnetic-quadrupole fields.

The loading of magneto-optic traps with neutral atoms directly from the gas phase has enormously stimulated the application of this new tool for atomic physics and quantum optics [1-3]. Currently the dynamic behaviour of atoms in a magneto-optic trap (MOT), where internal and external degrees of freedom are intimately coupled, is a field of intense research [4]. In particular it has been demonstrated that at the centre of such a trap sub-Doppler temperatures are obtained through the polarization gradient cooling mechanism [5, 6].

Another rather interesting aspect is the application of magnetic-quadrupole fields with large stiffness $b = \mathrm{d}B/\mathrm{d}z$, the magnetic-field gradient along the z-symmetry axis. At low temperatures such as those obtained by polarization gradient cooling a stiff magnetic-quadrupole trap could very tightly confine neutral atoms to a single centre in space. It even seems possible to reach the Lamb-Dicke regime which has recently been observed for atoms confined to the lowest-energy levels of an optical-dipole potential in the antinodes of standing-wave fields [7-9]. Magneto-optic compression of an atomic beam with permanent magnet assemblies has been demonstrated by Nellessen *et al.* [10] and also confinement of cold neutral atoms by magnetic-dipole forces only in an electrically driven magnetic quadrupole [11]. Laser cooling in a magnetic trap at the mK level has been reported by Helmerson *et al.* [12].

In this work we describe investigations on a magneto-optic trap, but with a large magnetic-field gradient. Such gradients are readily constructed from permanent magnets [13] up to the order of 1 T/cm. Although in our experiment the quadrupole fields are

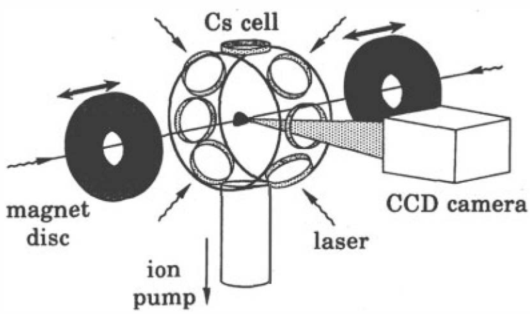

Fig. 1

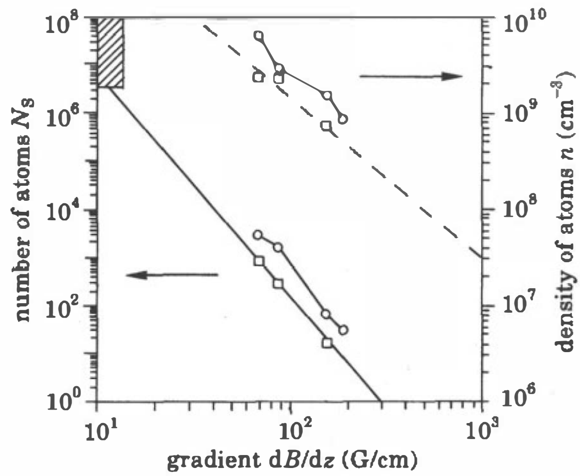

Fig. 2

Fig. 1. – Magneto-optic trap for cesium atoms in a gas cell. The quadrupole strength at the centre is adjusted by varying the separation of the magnetized discs. Atoms are slowed by radiation pressure from 6 laser beams.

Fig. 2. – Radiation pressure capture of cesium atoms from the gas phase: steady-state number of atoms N_S and density of atoms n as a function of stiffness $b = dB/dz$. Detuning is set for maximum fluorescence ($\Delta/\gamma \approx -2$) and found to vary little with b. The solid line follows the $b^{-14/3}$ scaling law for N_S, the dashed line follows $b^{-5/3}$ for n. The shaded area in the upper left corner marks parameters for standard magneto-optic traps. Note the different scales for N_S (left) and n (right). □ $I/I_0 = 4$, ○ $I/I_0 = 9$.

strong enough to compensate gravity and provide purely magnetic confinement, we will still relate to our system as «MOT».

We have employed the standard configuration for a magneto-optic trap [1-4], *i.e.* three pairs of properly polarized and counterpropagating light beams intersecting at the zero point of a magnetic quadrupole. A compact design (fig. 1) was chosen in order to apply permanent magnets without inserting them into the small vacuum chamber. Optical quality windows with AR-coating were glued onto a stainless-steel frame which was attached to an ion pump. We operated our cell typically with loading times of ~ 0.2 s corresponding to a few times 10^{-8} mbar of residual gas pressure [2]. Resonant light at $\lambda = 852$ nm for the cesium $6s_{1/2, F=4}$-$6p_{3/2, F'=5}$ transition was generated from a Ti : sapphire laser and transported to the cell via an optical fibre. It was split into three beams of 7 mm $1/e^2$ diameter with intensities corresponding to saturation parameters $s_0 = I/I_0 = 2\Omega_R^2/\gamma^2$ with $s_0 = 1.8 \div 92.0$ (Ω_R: Rabi frequency; $I_0 = 1.1\,\text{mW/cm}^2$: saturation intensity; $\gamma/2\pi = 5.3$ MHz: natural linewidth). In addition 2 mW from a laser diode tuned to the $6s_{1/2, F=3}$-$6p_{3/2, F'=4}$ transition were superposed along two arms of the trap to repump atoms from the $F = 3$ to the $F = 4$ ground-state hyperfine level. Both lasers were frequency-stabilized onto a saturated absorption spectrum obtained with a Cs gas cell.

With a pair of «anti-Helmholtz» current loops the regular MOT was obtained for gradients of order 10 G/cm. It showed all the properties regarding atom numbers and densities reported elsewhere [4]. Then we replaced the coils with a pair of permanently magnetized discs with opposing field orientation (fig. 1) closely resembling the anti-Helmholtz configuration. We used NdFeB material with a remanence force of $B_r = 1.2$ T and coercive field strength $H_c = 920$ kA/m. The quadrupole strength depends on the separation of the two magnetized discs and can be also calculated analytically at the percent level [13]. Two stacks of $1 \div 3$ discs with diameter $\varnothing = 50$ mm, a thickness of 5 mm and a 19 mm central bore provide field gradients from 60 to 450 G/cm at $(60 \div 90)$ mm separation.

The fluorescence of the trapped sample of atoms was measured with a calibrated photodiode as well as with a Peltier-cooled CCD camera. The imaging ratio was 1:1 for the camera resulting in a 15 μm spatial resolution limited by the pixel size. Due to spatial discrimination of the background fluorescence the camera was better suited for the detection of the weak fluorescence intensity from a small number of trapped atoms. Limited by fluorescence from the thermal cesium background at a few times 10^{-8} mbar the minimum detectable number of atoms in a 20 ms videoframe is currently on the order of 10 atoms. This is not a principal limit, and an improved vacuum system as well as a localized source of cesium atoms should enable us to detect a single atom within a 20 ms videoframe in the future.

We have measured the trap fluorescence intensity as a function of the stiffness b, the laser detuning $\Delta = (\omega - \omega_0)$, and the laser intensity I. The magnetic stiffness is conveniently measured in terms of $\beta = \mu_B b/\hbar\gamma = 0.26\,\text{cm}^{-1}((\mathrm{d}B/\mathrm{d}z)/(\text{G/cm}))$. For a given intensity we find the laser detuning for maximum sample fluorescence to be largely insensitive to the magnetic-field gradient. From the fluorescence intensity we can deduce the steady-state number N_S of trapped atoms by taking into account detuning and saturation from six laser beams in a Lorentzian resonance line shape. Zeeman shifts can be neglected, since the trapped atoms are collected in a region where $B \leq 0.5$ G. The most prominent observation is a rapid decrease in trap fluorescence and hence N_S as a function of b as shown in fig. 2. We have observed trapped atoms even at $b = 307$ G/cm, where quantitative measurements were not possible anymore.

Monroe *et al.* [2] have demonstrated that the equilibrium number of atoms in a MOT is determined by a balance of radiation pressure loading of low-velocity atoms from the background gas against losses mostly due to collisions with «hot» thermal atoms, as long as the density is not limited by multiple-photon–scattering processes [14]. The result can be summarized as $N_S = R_L \cdot \tau$, where R_L is the loading rate and τ the mean collision time with thermal atoms (τ is on the order of 0.2 s in our apparatus). Since magnetic energies are generally small, the collision time should not vary much with an increasing stiffness. Let us remark, though, that we do observe a slow increase of the trap loading time with quadrupole strength, as was noted previously by Gibble *et al.* [15].

The loading rate R_L, on the other hand, depends on both the geometric capture cross-section S of the trap and the maximum capture velocity v_{cap}, ($R_L \sim S v_{cap}^4$) [2]. For efficient slowing an atom has to undergo resonant excitation with a counterpropagating light beam. Gibble *et al.* [15] as well as Lindquist *et al.* [16] have shown that in a weak quadrupole the radiation pressure forces are effective across the full trap volume determined by the size of the laser beams, and hence the number of atoms grows in proportion to the cross-section of the beams. In a stiffer quadrupole field we can neglect Doppler detuning at low capture velocities compared to magnetic detuning and therefore an atom has to approach the centre within a radius of order $r_{cap} \lesssim |\Delta/\gamma\beta|$ for efficient deceleration. At constant detuning we then expect the geometric capture cross-section to decrease with $S = \pi r_{cap}^2 \sim b^{-2}$. As an example one calculates $r_{cap} \leq 1$ mm for $\Delta/\gamma = -2.5$ and $b = 100$ G/cm.

Maximum capture velocities for standard MOTs have usually been determined from numerical simulations [16]. We have instead analytically studied a simplified one-dimensional model yielding a relatively weak dependence $v_{cap} \sim b^{-2/3}$ of capture velocity *vs.* stiffness. The model treats atomic transition of the centre of the quadrupole in terms of a scattering problem and allows the determination of an upper limit for the capture velocity. For cesium atoms one calculates $v_{cap} \leq 4$ m/s for $b = 100$ G/cm. The moderate reduction of capture velocity and geometric capture cross-section translates into a much stronger reduction of the loading rate, $R_L \sim S v_{cap}^4 \sim b^{-14/3}$. The observed number of atoms N_S follows this scaling law surprisingly well and furthermore links our values to those obtained with standard low-field MOTs (fig. 2). Experimental and theoretical details concerning the optical capture process will be given in a separate publication [17].

The trapped cloud of atoms had a bell-shaped profile with radius z_0 (defined by the HWHM) along the z-symmetry axis and $r_0 \simeq \sqrt{2} z_0$ in the transverse direction for low saturation intensities. For higher saturation intensities at low field gradients we observe a transverse radius closer to $r_0 \simeq 2z_0$. The radii were measured by counting the number of pixels from the digitized CCD camera image. The density of atoms displayed in fig. 2 is determined from $n = N_S/V$ with $V = 4/3\pi r_0^2 z_0$. Note that the simple assumption that at constant intensity and detuning the trapped volume scales as b^{-3} or its linear dimension as b^{-1} gives a scaling law $n \sim b^{-5/3}$, which describes rather well the dependence of the observed densities on the magnetic gradient. The measured radii z_0 varied from more than 100 μm radius at 60 G/cm and high intensity ($s_0 > 90$) to only 15 μm for gradients above 200 G/cm and low intensity ($s_0 \approx 6$). The small radii have to be treated as an upper limit since the diameter of the cloud corresponds to 2 pixels only.

While the total number of trapped atoms drops from some 10^7 in regular MOTs to only 10 atoms at 207 G/cm, the density of trapped atoms decreases by just one order of magnitude (our experiment is by no means designed to achieve high densities).

Since it has been well established now [5, 6] that at the centre of low-field MOTs sub-Doppler temperatures due to polarization gradient forces exist, the observation of a rather tightly confined sample of trapped atoms raises the question whether sub-Doppler temperatures are occuring in stiffer magnetic traps as well.

Because we cannot switch off our magnetic fields in order to perform, for instance, time-of-flight measurements of kinetic energies [18, 19] we have tested this assumption by two different methods. In the first case we have quickly switched off the light fields and observed the expansion of the sample into the magnetic quadrupole. In the second case we have magnetically driven the atoms to determine restoring and damping forces in the trap.

By switching off all light within 100 μs, the atoms are released to the magnetic quadrupole. In order to determine the number of remaining atoms, we have strobed the centre of the quadrupole with the trapping laser for time intervals of 5 ms at various delays from 5 ms to 55 ms. During such a 5 ms illumination the trap is not reloaded, nor does the «free» cloud change its shape significantly.

Over the first few ms we observe an initial rapid decay of the number of trapped atoms by about 50% followed by a much slower decay over 50 ms. Since only atoms with angular momentum antiparallel to the magnetic-quadrupole field will experience a binding force towards the centre, we interpret the initial rapid decay as an ejection of atoms in unbounded magnetic sublevels. The following slower decay then can be attributed to losses of magnetically trapped atoms due to collisions with the background gas.

The initial decay is accompanied by an expansion of the cloud to an ellipsoidal shape with an expected axis ratio of roughly 2:1 and radius z_0 of about 100 μm, which according to the equipartition theorem corresponds to a temperature of the magnetically trapped sample of $T \approx 100$ μK for a gradient of $b = 140$ G/cm. This is a temperature within the cesium Doppler limit at 125 μK but measurements with this method are plagued by poor signal-to-noise ratios and large uncertainties.

In a low-field MOT Kohns *et al.* [6] have measured the response of the trapped atomic sample to an alternating homogeneous field superposed along the z-symmetry axis, which modulates the position of the zero point of the quadrupole field. A measurement of the phase

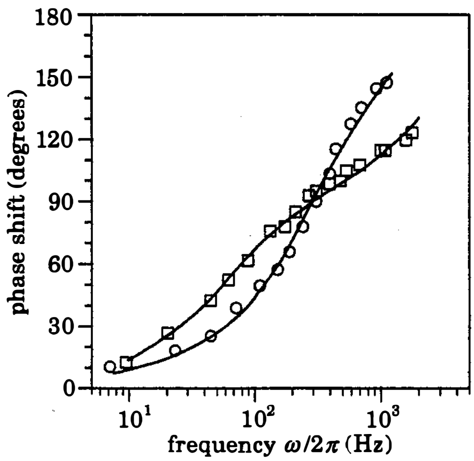

Fig. 3

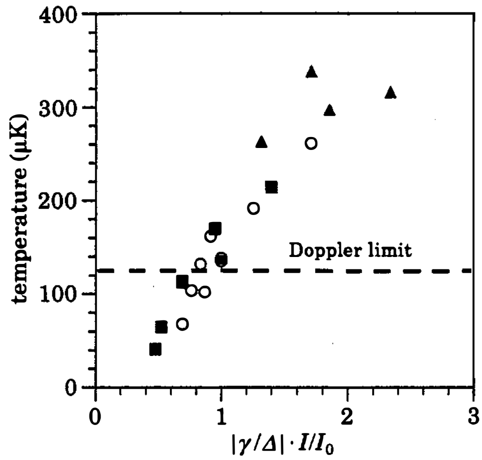

Fig. 4

Fig. 3. – Phase shift of the position oscillation as a function of magnetic drive frequency. The solid lines follow $\phi(\omega) = \text{arctg}\{\alpha\omega/m(\omega_0^2 - \omega^2)\}$ with $\omega_0/2\pi = (341 \pm 16)$ Hz, $\alpha = (2438 \pm 232)$ Hz at $\Delta/\gamma = -2$, $s_0 = 1.5$ and $\omega_0/2\pi = (371 \pm 17)$ Hz, $\alpha = (7270 \pm 628)$ Hz at $\Delta/\gamma = -3$, $s_0 = 2.2$. Quadrupole strength 63 G/cm. ○ $\Delta/\gamma = -2$, $s_0 = 1.5$; △ $\Delta/\gamma = -3$, $s_0 = 2.2$.

Fig. 4. – Temperature of the trapped sample of cesium atoms as a function of normalized inverse detuning. The Doppler limit for cesium is 125 μK. ■ 63 G/cm, $I/I_0 = 1.5$; ○ 92 G/cm, $I/I_0 = 2.0$; ▲ 92 G/cm, $I/I_0 = 3.6$.

of the position oscillation and the size of the trapped cloud allows the determination of the friction coefficient and restoring forces which can be used to assign a temperature from the equipartition theorem.

We have imaged the trapped cloud onto a quadrant photodiode (Siemens SFH 204) with 12 μm inactive separation. The differential photocurrent of the quadrant detector (two segments combined) is proportional to the displacement of the cloud. The amplitude of the forced position oscillation was always kept much below the linear dimensions of the cloud. With a reference voltage signal derived from a sampling resistor in series with the field excitation current the phase of the position oscillation was determined by a lock-in amplifier as a function of the excitation frequency $\nu = \omega/2\pi$ (fig. 3).

If we represent the trapped atoms by independent harmonic oscillators of mass m subject to a restoring force $F = -m\omega_0^2 z$ and friction force $F = -\alpha\dot{z}$, we can calculate the phase shift between a driving field $B = B_0 \cos(\omega t)$ and the forced oscillation $z(t) = a_z \cos(\omega t - \phi(\omega))$ from $\phi(\omega) = \text{arctg}\{\alpha\omega/m(\omega_0^2 - \omega^2)\}$. In order to determine ω_0, it is sufficient to find the frequency at which $\phi = 90°$. Once ω_0 is known, a temperature can be assigned using the spatial extent of the cloud with $k_B T = m\omega_0^2\langle z_0^2\rangle$. In fig. 4 we show that the temperature varies roughly as a linear function of the normalized inverse detuning $|\gamma/\Delta| \cdot I/I_0$ and clearly extends into the sub-Doppler regime with a lowest value of 40 μK. The scatter in our data is mostly a consequence of laser frequency jitter of order $\Delta\nu_{\text{r.m.s.}} \approx 1$ MHz.

In conclusion, we have observed radiation pressure capture of cesium atoms directly from the gas phase in magnetic-quadrupole fields directly from the gas phase up to a stiffness of $b = 307$ G/cm. In the optical-capture process an atom mainly interacts with the counter-propagating light beam. The strong reduction of the total number of trapped atoms, accompanied by only a moderate reduction in density, is consistent with both a decrease in capture velocity and geometric capture cross-section as a function of field gradient.

Once an atom is slowed down, it relaxes to a small trapping volume where the magnetic field as well as the Doppler shift are small and hence the interaction takes place simultaneously with all laser beams. In this region polarization gradient damping forces dominate atomic motion giving rise to temperatures well below the Doppler limit. Limited by technical constraints only, we have observed as few as 10 atoms confined to a volume of radius 15 μm in a 20 ms videoframe. Improvements of the experimental apparatus could provide the opportunity to observe single atoms (note that we expect a single atom in fig. 2 near $b = 300$ G/cm!) and perhaps also a very strong confinement on the wavelength scale near a single centre. According to our results direct capture from the gas phase does not seem to be practical, however. Precooling of the atomic sample in a separate conventional MOT or a rudimentary atomic beam combined with chirp cooling [20] are more promising routes to trapping and cooling also more substantial numbers of atoms in very strong quadrupole fields.

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REFERENCES

[1] RAAB E. L., PRENTISS M., CABLE A., CHU S. and PRITCHARD D. E., *Phys. Rev. Lett.*, **59** (1987) 2631.
[2] MONROE C., SWANN W., ROBINSON H. and WIEMAN C., *Phys. Rev. Lett.*, **65** (1990) 1571.
[3] GRISON D., LOUNIS B., SALOMON C., COURTOIS J. Y. and GRYNBERG G., *Europhys. Lett.*, **15** (1991) 149.
[4] For a recent review see: STEANE A. M., CHOWDHURY M. and FOOT C. J., *J. Opt. Soc. Am. B*, **9** (1992) 2142.
[5] STEANE A. M. and FOOT C. J., *Europhys. Lett.*, **14** (1991) 231.
[6] KOHNS P., BUCH P., SÜPTITZ W., CSAMBAL C. and ERTMER W., *Europhys. Lett.*, **22** (1993) 517.
[7] JESSEN P. S., GERZ C., LETT P. D., PHILLIPS W. D., ROLSTON S. L., SPREEUW R. J. C. and WESTBROOK C. I., *Phys. Rev. Lett.*, **69** (1992) 49.
[8] LOUNIS B., COURTOIS J.-Y., VERKERK P., SALOMON C. and GRYNBERG G., *Phys. Rev. Lett.*, **69** (1992) 3029.
[9] HEMMERICH A. and HÄNSCH T. W., *Phys. Rev. Lett.*, **70** (1993) 410.
[10] NELLESSEN J., WERNER J. and ERTMER W., *Opt. Commun.*, **78** (1990) 300.
[11] MIGDALL A. L., PRODAN J. V., PHILLIPS W. D., BERGEMAN T. H. and METCALF H. J., *Phys. Rev. Lett.*, **54** (1985) 2596.
[12] HELMERSON K., MARTIN A. and PRITCHARD D. E., *J. Opt. Soc. Am. B*, **9** (1992) 1988.
[13] FRERICHS V., KAENDERS W. G. and MESCHEDE D., *Appl. Phys. A*, **55** (1992) 242.
[14] SESKO D., WALKER T., MONROE C., GALLAGHER A. and WIEMAN C., *Phys. Rev. Lett.*, **63** (1989) 961.
[15] GIBBLE K. E., KASAPI S. and CHU S., *Opt. Lett.*, **17** (1992) 526.
[16] LINDQUIST K., STEPHENS M. and WIEMAN C., *Phys. Rev. A*, **46** (1992) 4082.
[17] HAUBRICH D., HÖPE A. and MESCHEDE D., submitted to *Opt. Commun.*
[18] LETT P. D., WATTS R. N., WESTBROOK C. I., PHILLIPS W. D., GOULD P. L. and METCALF H. J., *Phys. Rev. Lett.*, **61** (1988) 169.
[19] SALOMON C., DALIBARD J., PHILLIPS W. D., CLAIRON A. and GUELLATI S., *Europhys. Lett.*, **12** (1990) 683.
[20] CABLE A., PRENTISS M. and BIGELOW N. P., *Opt. Lett.*, **15** (1990) 507.