Behavior of atoms in a compressed magneto-optical trap

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We investigate the behavior of a cloud of atoms in a magneto-optical trap, which—after collection—is compressed when the field gradients of the trap magnetic field are increased. We measure sizes and shapes of the atom cloud as a function of laser detuning, magnetic field gradient, and number of trapped atoms. A transient density increase of more than an order of magnitude has been achieved. Moreover, reproducible Gaussian density distributions are observed at large detunings and intermediate magnetic-field gradients, permitting an accurate determination of density.

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The ability to capture and store atoms from a vapor in a magneto-optical trap[1,2] (MOT) has stimulated a broad field of research in atomic physics and quantum optics including cold collisions and studies of quantum effects in a dense, cold atom cloud.[3–5] Many of these experiments require high trapped-atom densities. In this paper we investigate the properties of a trapped-atom sample that we collected using low magnetic-field gradients and subsequently compressed increasing the gradients of the confining magnetic field. This two-step procedure avoids the drawback of low collection efficiency associated with high magnetic-field gradients in the MOT. Hence we are able to maintain a large number of atoms and to achieve a transient but substantial increase in the density of the atom cloud in the highly compressed magneto-optical trap (CMOT).

The density and the temperature of optically trapped atoms have been studied in detail.[6–8] Temperatures well below the Doppler limit have been observed and associated with polarization gradient cooling.[9–11] Density studies have uncovered two density-limiting mechanisms. For small numbers of atoms the density of the trapped atom cloud is given by the thermal motion of each individual atom in the trapping potential. Considering the trapping potential to be a simple harmonic well, we see that this motion causes the atom cloud to adopt a Gaussian density distribution with a root-mean-square radius $\langle r_i \rangle$ given by the equipartition theorem,

$$\tfrac{1}{2} k_B T_i = \tfrac{1}{2} \kappa_i \langle r_i \rangle^2 , \tag{1}$$

where T_i is the temperature, k_B is the Boltzmann constant, κ_i is the spring constant of the trap, and $i = x, y, z$. In MOT's the cloud is usually treated as being equilibrated ($T_x = T_y = T_z \equiv T$), and the spring constants in the horizontal and the vertical directions fulfill the relation $2\kappa_x = 2\kappa_y = \kappa_z \equiv \kappa$. Hence for N trapped atoms the peak density n_p is given by

$$n_p \equiv \frac{N}{\sqrt{(2\pi)^3}\,\langle r_x \rangle \langle r_y \rangle \langle r_z \rangle} \sim N \left(\frac{\kappa}{k_B T} \right)^{3/2} . \tag{2}$$

The second major density limitation arises from the reradiation of the photons within the cloud and from the attenuation of the laser beams. For large numbers of atoms the density is determined by the counterbalance between the force related to these effects and the trapping force and is calculated[12] to be proportional to

$$n_r \sim \frac{\kappa}{I \sigma_L (\sigma_R - \sigma_L)} , \tag{3}$$

where I denotes the laser intensity and σ_L and σ_R are the cross sections for absorbing a photon from the laser field and for absorbing a reradiated photon, respectively. Note that the density is independent of position r and is therefore constant inside the cloud.

Collisions between the trapped atoms affect the lifetime of the trapped atoms and thus the number that can be accumulated in a MOT. The number of trapped atoms will in turn affect the density. But since in our experiments atom collection and density compression are accomplished at different times, we do not include collisions in our discussion of density.

From relations (2) and (3) it follows that the maximum densities in the temperature-limited and in the reradiation-limited regimes are proportional to $\kappa^{3/2}$ and κ, respectively. Our experimental approach is to modify the spring constant κ to achieve higher densities.

Because the spring constant is proportional to the magnetic-field gradients $\partial B / \partial r_i$, it is desirable to operate the trap at large gradients when aiming for high densities. However, Höpe *et al.*[13] observed that increasing the gradients leads to a strong decrease of the loading rate $R \sim (\partial B / \partial r_i)^{-14/3}$ at which atoms are captured from the vapor gas. They reported a decrease in the number of trapped atoms from 10^7 for a normal MOT with field gradients of the order of 10 G/cm down to 10 atoms for a vertical gradient of 207 G/cm. In contrast, for the measurements described in this paper we first collect atoms from the vapor gas, using low field gradients, and then rapidly increase the field gradients. This separation of the collection and the compression processes allows us to achieve high densities for large numbers of atoms.

In addition it can be advantageous to increase the detuning δ_L of the trapping laser beams. In the reradiation limit large detunings are expected to decrease the

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repelling reradiation forces strongly ($\sim\delta_L^{-4}$), while the decrease of the trapping force only scales as δ_L^{-1} in the central, low-magnetic-field region of the trap and as δ_L^{-3} in the outer region.[7,11] Thus for a given number of atoms the new balance between these forces favors higher densities. Although in the temperature-limited regime larger detunings have been found to lead to lower temperatures, the actual densities depend on the ratio between the temperature and the (detuning-dependent) spring constant according to relation (2). Steane *et al.*[7] suggest that the densities in the temperature-limited regime are in fact independent of detuning.

For trapping ^{85}Rb atoms from a vapor gas we employ the standard configuration of a MOT, i.e., three pairs of appropriately polarized, counterpropagating laser beams intersecting in the zero point of a magnetic quadrupole field, which is created by a pair of coils in an anti-Helmholtz configuration. Light from a diode laser drives the $5s\ ^2S_{1/2}(F=3) \rightarrow 5p\ ^2P_{3/2}(F'=4)$ transition in ^{85}Rb (natural linewidth $\Gamma/2\pi = 6$ MHz) at a wavelength of 780 nm with a peak intensity of 15 mW/cm^2 in each of the six beams (FWHM beam size, 7 mm). To provide hyperfine pumping we overlap the light emitted from a second laser with the trapping laser beams and repump the atoms on the $5s\ ^2S_{1/2}(F=2) \rightarrow 5p\ ^2P_{3/2}(F'=3)$ transition. At a measured effective saturation parameter of $S \approx 13$ we are able to trap up to 10^8 atoms with a loading rate of 10^7 atoms/s. The $1/e$ time constant for atoms to remain in the trap under these conditions is 9 s. The number of trapped atoms can be deduced from measuring a known fraction of the emitted fluorescent light on a calibrated photodiode. The accuracy in determining the absolute number of atoms is about $\pm 20\%$, whereas the measurements on relative numbers at a fixed detuning are better than $\pm 5\%$. Information on the size of the cloud is obtained by observation of the fluorescent light with a CCD camera and analysis of the obtained video pictures of the cloud with a computer. (More precisely, we store data from only the one horizontal line and the one vertical line that include the peak of the atom cloud.) The resolution of this detection scheme is better than 20 μm.

Initially we set the detuning to -9 MHz and the field gradient to $\partial B/\partial r_z (=2\partial B/\partial r_{x,y}) = 11$ G/cm to optimize the collection efficiency of the MOT. After collection for typically 0.5 s, the cloud contains 6×10^6 atoms and exhibits horizontal and vertical FWHM sizes of 0.8 and 0.3 mm, respectively, giving a density of 2×10^{10} cm^{-3}. Note that in the uncompressed MOT the shape of the cloud and hence also the ratio between the horizontal and the vertical cloud sizes is significantly distorted by intensity inhomogeneities of the trapping laser beams. We then jump the detuning to various values. One millisecond after having jumped the detuning, we ramp the magnetic field in five steps over 5 ms to field gradients $\partial B/\partial r_z$ between 11 and 228 G/cm. After each step the magnetic field settles within 0.1 ms. Details of stepping time and step size are not critical unless the gradient is jumped in a single step; in this case a significant loss of atoms is observed. After establishing a new magnetic-field gradient, we allow the cloud to equilibrate for 20 ms before we measure sizes, shapes, and numbers of atoms of the cloud.

In the measurements described first, we concentrate on the influence of the laser detuning and do not change the field gradients. We collected atoms from the vapor gas for 0.5 s ($\rightarrow N \approx 6 \times 10^6$ atoms) and then jumped the laser detuning from the collection detuning $\delta_L = -9$ MHz to values of -19, -32, and -44 MHz at a constant vertical field gradient of $\partial B/\partial r_z = 11$ G/cm. We observe that for these low field gradients the cloud exhibits an irregular non-Gaussian shape. Hence the measured sizes and therefore also the densities in this regime have to be considered estimates. We believe that the irregular shapes are due to an increased sensitivity to laser field inhomogeneities at lower field gradients. When we jump the detuning from -9 to -19 MHz, the cloud sizes decrease to ≈ 0.5 mm (FWHM) in the horizontal plane and ≈ 0.3 mm (FWHM) in the vertical direction. For larger detunings the cloud size does not decrease any further. Since the number of atoms in the trap stays approximately constant as the detuning is jumped, the estimated densities increase by a factor of 3 in going from -9 to -19 MHz (Ref. 14) but do not increase for further detuning. The density's insensitivity to detuning above -19 MHz coincides with the predictions in Ref. 7 for a cloud that is density limited by its temperature; i.e., for large detunings ($4\pi\delta_L \gg \Gamma$) the cloud size should become independent of the detuning.[15]

We now describe measurements in which we ramp the field gradient after we jump the laser detuning to -44 MHz. For this detuning and for vertical field gradients of up to 60 G/cm all atoms are compressed into a narrow peak that exhibits a Gaussian shape, permitting an accurate determination of the densities. For $\partial B/\partial r_z >$ 60 G/cm, however, this narrow peak (central feature) is surrounded by a diffuse cloud of atoms. While the position and the shape of the diffuse cloud strongly depend on the alignment and the imbalance of the laser beams, the position, the shape, and the size of the central feature are relatively insensitive to slight misalignment. The existence of the two parts of the atom cloud and their differing behavior is predicted in Refs. 7 and 11. This result is consistent with a picture of the central feature's being compressed by a strong, position-dependent polarization gradient force, which has been found to be the dominant trapping force for low magnetic fields, i.e., in the trap center. On the other hand, in the large magnetic fields beyond the trap center this force is suppressed, and only the spontaneous force remains, which allows the atoms to spread into a sparse cloud. In addition, even the force of the magnetic field on the magnetic moments of the atoms may be nonnegligible in this region. The precise roles of the individual forces, however, require further investigation. Figure 1(a) shows the FWHM of the central feature in the horizontal and the vertical directions as a function of the vertical field gradient $\partial B/\partial r_z$ for the detuning of $\delta_L = -44$ MHz. The data follow the dependence expected from Eq. (1) for a constant temperature, i.e., $\langle r_i \rangle \sim (\partial B/\partial r_i)^{-1/2}$, and the ratio of the sizes in the horizontal and the vertical directions is close to $\sqrt{2}$ (see the dashed curves in Fig. 1). The fraction of atoms in the central feature can be estimated from the video data, and the total number of atoms in the trap is deduced from the photodiode signal. For the detuning of -44 MHz we observe no measurable decrease of the total number of atoms during compression, and the lifetime of the atoms in the CMOT is found to be of the order of seconds. Al-

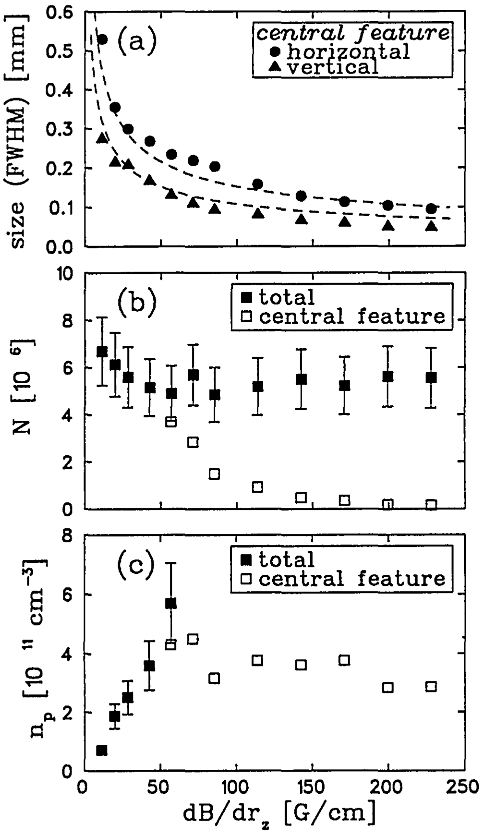

Fig. 1. (a) Horizontal and vertical sizes, (b) number of atoms, and (c) peak densities shown as a function of the vertical magnetic field gradient $\partial B/\partial r_z$ ($=2\partial B/\partial r_{x,y}$). The detuning was set to −44 MHz. The filled symbols in (b) and (c) represent the actual parameters of the cloud, and the open symbols are an estimate of the fraction of atoms in the central feature and the peak densities connected to this estimated fraction (see text). The dashed curves in (a) are a fit to an inverse-square-root dependence with a forced ratio of $\sqrt{2}$ between the radial and the axial sizes.

though the total number of atoms stays approximately constant as the magnetic-field gradient changes, the fraction of atoms in the central feature starts to decrease for gradients larger than 60 G/cm [Fig. 1(b)]. Knowing the total number of atoms, the Gaussian width of the central feature, and having estimated the fraction of atoms in the central feature, we calculate the peak density n_p shown in Fig. 1(c) as a function of the vertical magnetic-field gradient. For fields smaller than 60 G/cm, peak densities as high as 5×10^{11} cm^{-3} have been achieved. This corresponds to an increase in density of more than an order of magnitude compared with the density of a normal MOT ($n_p \approx 2 \times 10^{10}$ cm^{-3}). We point out that for this large detuning the CMOT exhibits high densities with long lifetimes and Gaussian density distributions; therefore it is an ideal tool to use in studies that require high densities and for which a precise knowledge of this density is desirable, such as investigations of cold collisions.[5]

Analogous measurements have been performed with smaller detunings of −9 (i.e., the normal MOT detuning), −19, and −32 MHz. In general we find lower densities and less Gaussian-shaped curves in these cases. The FWHM's deviate significantly from the magnetic-field gradient dependence expected for the temperature-limited sizes $\sim(\partial B/\partial r_i)^{-1/2}$ as well as for reradiation-limited sizes $\sim(\partial B/\partial r_i)^{-1/3}$. On the other hand, we observe that the sparse cloud surrounding the central feature diminishes with decreasing detuning. In addition, we find that the total number of atoms remaining in the trap after compression also decreases; for the smallest detuning and the largest field gradient this loss amounts to 65%. The loss of atoms occurs on two time scales: a rapid loss of atoms, which is not yet understood, is observed mainly during compression, followed by a slow decay with time constants between ≈50 ms ($\partial B/\partial r_z = 228$ G/cm, $\delta_L = -9$ MHz) and seconds (both the rapid loss and the slow decrease become less pronounced with larger detunings and smaller gradients). The slow loss of atoms is likely to be caused by intratrap collisions, which are dependent on the laser detuning in a manner consistent with light-assisted collisions.[16] In any case the lifetime of the CMOT would be plenty long enough to allow for the transfer of the compressed atom cloud to a purely magnetic trap, in which there would be no light-assisted collisions and where further cooling, for instance, by evaporation,[17] seems feasible.

In a further series of measurements the collection time τ and hence the total number of atoms is varied from $\tau = 0.1$ s to $\tau = 30$ s, corresponding to $3 \times 10^6 \leq N \leq 8 \times 10^7$. After collection of the atoms the detuning is jumped to $\delta_L = -32$ MHz, and the magnetic field gradient is ramped to $\partial B/\partial r_z = 85$ G/cm. We find that both the sizes r_i [Fig. 2(a)] and the number of atoms in the central feature N_{cf} [Fig. 2(b)] increase for small total numbers of atoms N in the trap. Analyzing the data yields a dependence of $r_i \sim \sqrt[3]{N_{cf}}$, which is expected in the reradiation-limited regime according to relation (3); in fact, the densities derived from the shown sizes and numbers are approximately equal and amount to $n \approx 2 \times 10^{11}$ cm^{-3} [Fig. 2(c)]. For $N \geq 2 \times 10^7$ any additionally loaded atoms are dispersed into the sparse cloud around the central feature, so the number of atoms in the central feature as well as its size do not increase any further. We believe that the limit on the size of the central feature, and therefore on the number of atoms compressed therein, arises from a suppression of polarization gradient forces for large radii. As is mentioned above, the dominant role of these forces in the center of an ordinary MOT is pointed out in Refs. 7 and 11. Steane *et al.*[7] suggest that the high gradients, however, give rise to Larmor frequencies, which then become comparable with the optical pumping rate and the ac Stark shifts at radii small enough to be inside the actual cloud. The occurrence of large magnetic fields close to the trap center will inhibit the polarization-gradient forces even at these small radii, and in this way could lead to a limitation of the size of the strongly compressed central feature. We find the size limit of the central feature and the existence and properties of the diffuse cloud an intriguing problem worthy of further theoretical as well as experimental studies.

In summary, we have investigated the behavior of an atom cloud in a magneto-optical trap that is suddenly exposed to high magnetic-field gradients. We have studied sizes and shapes of the atom cloud as a function of the amplitude of the magnetic-field gradient, of the laser detuning, and of the total number of atoms. For large detunings and intermediate field gradients, peak densities as high as 5×10^{11} cm^{-3} are achieved, corresponding to a

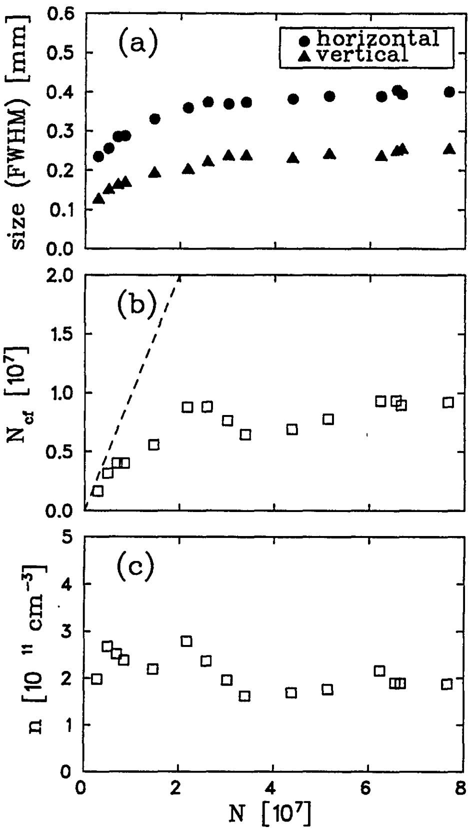

Fig. 2. Properties of the central feature shown as a function of the total number of atoms N collected in the trap. (a) The horizontal and vertical sizes, (b) the number of atoms in the central feature N_{cf}, and (c) the peak densities are displayed. For these measurements the detuning of the CMOT is -32 MHz, and the vertical magnetic field gradient is 85 G/cm. The dashed line in (b) illustrates the behavior if all atoms were in the central feature ($N_{cf} \equiv N$). Note the apparent limit on the sizes and numbers of atoms in the central feature for $N \gtrsim 2 \times 10^7$.

density increase of more than an order of magnitude compared with the density of a normal MOT. Although this density increase is in principle of a transient nature, we observe lifetimes of the order of seconds for large detunings. Moreover, we find that the density distribution in this highly compressed MOT is purely Gaussian for large detunings and intermediate field gradients. Therefore in this regime the CMOT appears to be an ideal tool for investigations that require an accurate knowledge and high values of the density, such as studies of cold collisions. Furthermore, first measurements indicate that the transfer of atoms from the normal MOT into a magnetic trap can be significantly improved by this method of compression. The resulting high densities in the magnetic trap are an important step toward the goal of evaporative cooling in the magnetic trap, which might eventually lead to the observation of collective effects such as Bose–Einstein condensation of the weakly interacting atom sample.[3]

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REFERENCES AND NOTES

1. E. L. Raab, M. Prentiss, A. Cable, S. Chu, and D. E. Pritchard, Phys. Rev. Lett. **59,** 2631 (1987).
2. C. Monroe, W. Swan, H. Robinson, and C. Wieman, Phys. Rev. Lett. **65,** 1571 (1990).
3. C. Wieman, C. Monroe, and E. Cornell, in *Proceedings of the Tenth International Conference on Laser Spectroscopy,* M. Ducloy, E. Giacobini, and G. Camy, eds. (World Scientific, Singapore, 1992), p. 77.
4. D. E. Pritchard, K. Helmerson, and A. G. Martin, in *Proceedings of the Eleventh International Conference on Atomic Physics (ICAP XI),* S. Haroche and J. C. Gay, eds. (World Scientific, Singapore, 1989), p. 179.
5. See also L. Marcassa, V. Bagnato, Y. Wang, C. Tsao, J. Weiner, O. Dulieu, Y. B. Band, and P. S. Julienne, Phys. Rev. A **47,** R4563 (1993).
6. K. Lindquist, M. Stephens, and C. Wieman, Phys. Rev. A **46,** 4082 (1992).
7. A. M. Steane, M. Chodhurry, and C. J. Foot, J. Opt. Soc. Am. B **9,** 2142 (1992).
8. See also W. Ketterle, K. B. Davis, M. A. Joffe, A. Martin, and D. E. Pritchard, Phys. Rev. Lett. **70,** 2253 (1993).
9. A. M. Steane and C. J. Foot, Europhys. Lett. **14,** 231 (1991).
10. C. D. Wallace, T. P. Dinneen, K. Y. N. Tan, A. Kumarakrishnan, P. L. Gould, and J. Javanainen, University of Connecticut, Storrs, Mansfield, Conn. 06269 (personal communication).
11. J. Werner, H. Wallis, and W. Ertmer, Opt. Commun. **94,** 525 (1992).
12. D. W. Sesko, T. G. Walker, and C. E. Wieman, J. Opt. Soc. Am. B **8,** 946 (1991).
13. A. Höpe, D. Haubrich, G. Müller, W. G. Kaenders, and D. Meschede, Europhys. Lett. **22,** 669 (1993).
14. It has been brought to our attention that an increase in density for larger detunings was also observed by C. Salomon and co-workers, Hertzienne de l'École Nationale Supérieure, Laboratoire de Spectroscopie, 75231 Paris Cedex, France (personal communication); M. Drewsen, Ph. Laurent, A. Nadir, G. Santarelli, A. Clairon, Y. Castin, D. Grison, and C. Salomon, "Investigation of sub-Doppler cooling effects in a cesium magneto-optical trap," submitted to Appl. Phys. B.
15. The calculations in Ref. 7 are valid only for small saturation parameters and for a $J = 0 \rightarrow J' = 1$ transition. Hence we cannot infer any quantitative statement by comparing our results directly with these calculations.
16. D. Sesko, T. Walker, C. Monroe, A. Gallagher, and C. Wieman, Phys. Rev. Lett. **63,** 961 (1989).
17. N. Masuhara, J. M. Doyle, J. C. Sandberg, D. Kleppner, T. J. Greytak, H. F. Hess, and G. P. Kochanski, Phys. Rev. Lett. **61,** 935 (1988), and references therein.