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Large atom-density change at constant temperature by varying trap anisotropy in a dilute magneto-optical trap

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Abstract

We show that it is possible to vary the number density of a trapped sample of laser-cooled atoms in a dilute magneto-optical trap by over an order of magnitude while keeping the temperature constant. This can be accomplished by varying the relative intensity of the trapping laser beams, such that the total intensity (sum of all six beams) remains fixed. This makes the trap anisotropic, i.e., causes the shape of the cloud to be deformed, but leaves the total number N of trapped atoms unchanged, thus leading to a change in the number density. The temperature does not change because the total laser intensity, the laser detuning, and all other trap parameters stay fixed throughout the experiment.

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Cold trapped atoms – cooled by laser beams and confined by magnetic field gradients in a magneto-optical trap (MOT) – serve as a starting point for a vast variety of exciting experiments in atomic, molecular, and optical physics. For example, at this year's DAMOP [1] conference, nearly 50% of all presentations (covering diverse topics such as spectroscopy, collisions, molecule formation, plasmas, quantum entanglement and quantum information, and atom optics) relied on the initial preparation of magneto-optically trapped cold atoms. A well-known feature of the MOT is that the trap parameters, such as temperature T, trapped atom-number N and trapped atom-density n, are strongly interconnected [2]. This means that changes in the laser intensity, detuning, beam size, or in the magnetic field gradient, generally lead to simultaneous changes in T, N, and n.

However, for many applications it may be desirable to independently vary one of T, N, or n without affecting the other two. Two important examples are experiments which investigate the

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dynamics of cold atoms by analyzing correlations in the scattered light, and experiments which investigate collisions between laser-cooled atoms by measuring "trap-loss" rates (i.e., the rate of ejection of atoms from the trap, owing to some of the internal energy of the atoms being converted to kinetic energy during the collision). First, in the case of correlation measurement of the scattered light it has been shown that the shape of the correlation function depends on the residual Doppler broadening of the cold atoms, and is therefore highly sensitive to changes in the temperature T of the trapped atoms [3]. Hence, any attempt to exploit correlation spectroscopy to investigate, for instance, radiation trapping in trapped samples at different optical depths [4], or atomic transport between potential wells in an optical lattice at different well-depths [5], depends critically upon the ability to hold T constant while varying other trap parameters like the density n, or the laser intensity, or laser detuning. Second, in the case of cold collisions it is well known that the long collision times lead to the possibility of the collision dynamics being affected by absorption–emission processes, meaning that these collisions are very different from usual atomic collisions [6]. The cross-section for these novel collisional processes can be determined from a measurement of the trap-loss rate (which depends upon both n and T) [7]. In this situation the ability to vary just one trap parameter while holding the other constant offers a convenient method of systematically measuring the trap-loss rate as a function of the various trap parameters.

Achieving independent control of the various trap parameters is not straightforward for, despite the wide use of the MOT as an inexpensive way to produce atomic samples with temperatures below 1 mK [8], the detailed physics of the typical MOT is far from being completely understood. This is because of the complexity of the atom-laser field coupling and the atom-atom coupling for multi-level atoms subjected to the effects of polarization gradients and cold collisions in a three-dimensional configuration of the laser beams. The conventional approach to understanding MOT dynamics is to construct, by careful observation, semiempirical scaling laws inter-relating the various parameters of the trap [2,9]. Our experiments are conducted on a cold dilute trapped atomic sample of about 10^7 atoms with densities in the 10^8–10^9/cm^3 range. Past work [10] informs us that $N > 10^5$ means that our sample is in the so-called multiple scattering regime, where the reabsorption of scattered photons becomes important. In fact, by measuring the intensity correlations of the light scattered from a cold atom sample of $\sim 10^7$ atoms, we recently found evidence of radiation trapping at the densities used in this paper [4]. This is true even though the densities in [4] and in this paper are up to two orders of magnitude less than that in previous treatments [10–12] of multiple scattering in cold atom clouds. A key feature of the multiple scattering regime is that the density becomes independent of the trapped atom number so that the cloud merely grows in volume as more atoms are added, maintaining a constant n independent of N [10]. In this case, it has been demonstrated that for fixed laser intensity, the cloud temperature T scales with N and the laser detuning δ as follows [2]:

$$T \propto N^{1/3}/\delta. \quad (1)$$

It follows that if one manipulates the cloud shape at a fixed detuning such that n changes but not N, then one may cause significant density changes at constant temperature. The use of trap anisotropy as a "control knob" is a relatively unexplored topic in MOT physics. Very recently, creating trap anisotropy has been explored as a technique to circumvent effects of multiple scattering in cold atom clouds [13].

In this paper we show that it is possible to use trap anisotropy to vary the trapped atom number density *while keeping the temperature constant*. We present experimental evidence for a change in the number density of a cold dilute trapped atomic sample by just over an order of magnitude, at constant temperature. Specifically, we vary n from 1.9×10^9 to 1.6×10^8/cm^3 for a trapped sample of ^{85}Rb atoms while keeping T fixed at 55 ± 5 μK. Because typical "garden-variety" alkali MOT's operate at temperatures of several tens of μK, and densities of 10^7–10^{11}/cm^3 we expect our results to be widely applicable. We show that this change in n at constant T is accomplished with a mild change in the aspect ratio of the cloud by varying the relative intensity of the trapping laser beams, but keeping the total number N of trapped atoms unchanged. The number density changes because the shape of the cloud is deformed from spherical to elliptical, thus altering the cloud volume. We speculate that the observed temperature is constant because the total intensity of all six trapping laser beams, the laser detuning, and all other trap parameters are kept fixed. We show that alternative attempts to change the number density of the cloud, for example, by altering the trap laser beam size or intensity or detuning, or the magnetic field gradient, result in a significant change in temperature and/or only a moderate change in the density.

We employ a standard vapor-loaded σ^+–σ^- magneto-optical trap (MOT) of ^{85}Rb, produced inside an ion-pumped stainless steel vacuum chamber ($\sim 10^{-9}$ Torr), using light from an external-cavity-stabilized diode laser operating 1–3 natural linewidths below the $5S_{1/2}(F = 3) \rightarrow 5P_{3/2}(F' = 4)$ transition of ^{85}Rb. As per usual practice, the light output from this laser is split into three beams using a pair of beamsplitters, one of which is polarizing. The relative intensity of the three beams is adjusted by rotating a half-wave plate inserted just before the polarizing beamsplitter. The three beams are directed along the x, y, and z directions, respectively, then retroreflected to yield the six trapping beams. A pair of current-carrying coils external to the vacuum chamber provides a magnetic field gradient of 8 G/cm for the MOT along, say, the x direction. In most MOTs', the intensity of the x-trapping beams is typically kept at half the intensity of the y and z-trapping beams to compensate for the B-gradient in the x-direction being twice that in the y and z directions. In our experiment, the total laser intensity (sum of all six beams) at the position of the trapped atoms is 3.6 mW/cm^2 and stays fixed throughout the experiment.

When the relative intensity ratio of the x:y:z trapping beams is 20:40:40 as described above, our trapped atom cloud is approximately spherical with a diameter of 2.4 mm. The diameter of the trapping laser beams was 15 mm in this case. To measure the cloud density, we measure the absorption of a weak on-resonance (with the $5S_{1/2}$-$(F = 3) \rightarrow 5P_{3/2}(F' = 4)$ trapping transition) probe beam propagating through the cloud. The output intensity I for the probe beam is related to the input intensity I_0 by $I = I_0 e^{-n\sigma l}$, where σ is the resonant absorption cross-section (2.91×10^{-11} cm^2 for this transition) and l is the length of the cloud traversed by the probe. For a roughly spherical cloud l is simply the cloud diameter. The temperature of the atoms is measured with a standard time-of-flight (TOF) technique, using the fluorescence signal from a probe beam located 10 mm below the position of the cloud of trapped atoms, and is found to be 55 ± 5 μK throughout the experiment. We only measure the temperature along this one direction. It would be instructive to measure the temperature along other directions as well, even though our cloud is only mildly anisotropic.

In Fig. 1 we plot the measured number density n and temperature T as a function of the intensity of the trapping beams in the x-direction. The y and z beams are of the same intensity. The plot shows that in our MOT the highest density is obtained

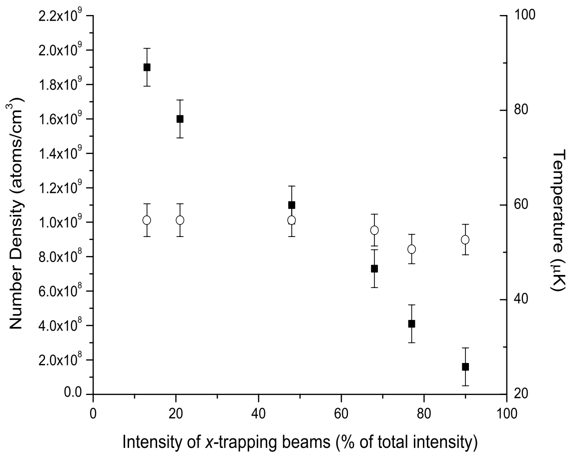

Fig. 1. Dependence of number density (filled squares) on relative intensity of the trapping beams. The x-axis is the percentage of total intensity in the two x-trapping beams. The y and z beams are of the same intensity. As shown in the figure, the highest (lowest) density is obtained for a relative x:y:z intensity ratio of 12:44:44 (90:5:5). The number density changes by over an order of magnitude while the temperature (hollow circles) stays constant at 55 ± 5 μK.

when the relative intensity ratio of the x:y:z trapping beams is 12:44:44, and the lowest density is obtained for a relative intensity ratio of 90:5:5. We see that at a relative intensity ratio of 20:40:40 the density is $1.6 \times 10^9/\text{cm}^3$, which then rises slightly to $1.9 \times 10^9/\text{cm}^3$ at 12:44:44. The density will obviously fall back down as the x-intensity approaches zero. Note that changing the relative intensity of the trapping beams from the 20:40:40 configuration causes the cloud shape to become asymmetric. At the lowest density, the two-dimensional image of the cloud is an ellipse with a minor diameter of 1.8 mm and a major diameter approximately three times longer. We assume the density to be uniform throughout the cloud [2]. The total trapped atom number N was monitored by imaging the fluorescence within a known solid angle from the cloud onto a photodiode, and was determined to be about 10^7 throughout the measurements in Fig. 1. Note that the total laser intensity stays fixed while the relative intensities of the trapping beams are varied. This, we speculate, is why the trapped atom number N and the temperature T stay relatively constant throughout the experiment. However, Fig. 1 shows there is a clear change in the number density. Fig. 1 is the main result of this paper.

In Figs. 2–4 we plot the dependence of number density n and temperature T on trapping beam size, trap laser detuning, and magnetic field gradient, respectively. As described below, in none of these figures do we see as large a change in number density for as little a change in temperature as in Fig. 1.

In Fig. 2 we investigate the change in number density n and temperature T as we vary the trap laser beam size from 15 mm in diameter to 10 mm. The x-axis of this plot is the trap volume (not the cloud volume) formed by the intersection region of the trapping laser beams. We see that T does not change by much, from about 49 to 62 μK, but neither does the measured number density. This is consistent with previous work by others [2,9] in that changing the trap volume changes the total number N of atoms trapped (by about a factor 2 in our case), leading to a gradual change in temperature according to the $N^{1/3}$ dependence in Eq. (1). The number density, however, is

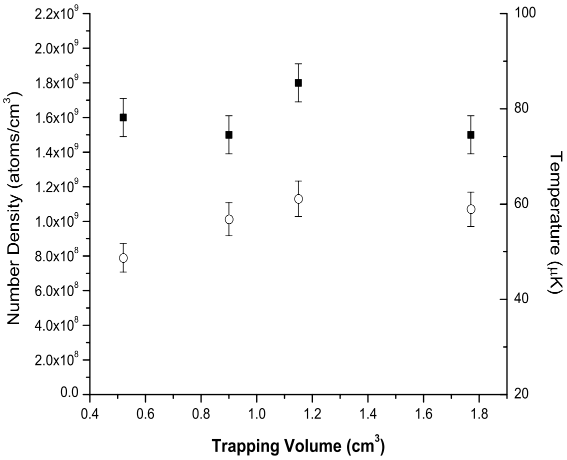

Fig. 2. Dependence of number density (filled squares) and temperature (hollow circles) on the size of the trapping laser beams. The trapping volume is the spherical volume of intersection of the six trapping beams. n and T show only a modest change.

expected to be independent of N in the multiple scattering regime [10].

Fig. 3 shows the effect on n and T as the trap laser's detuning δ is varied from -1.4Γ to -2.3Γ, where Γ is the natural linewidth (5.9 MHz for ^{85}Rb). We observe that T falls from 66 to 55 μK

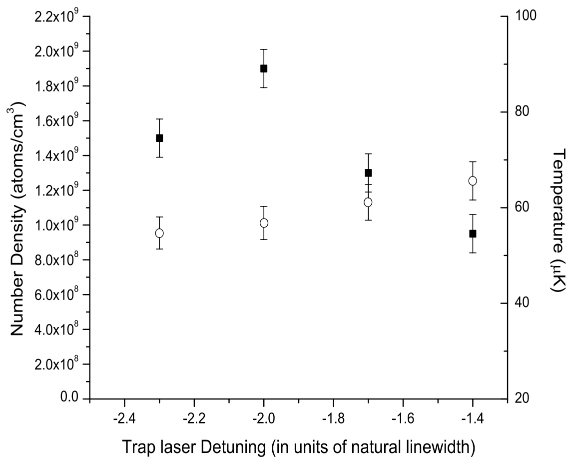

Fig. 3. Dependence of number density (filled squares) and temperature (hollow circles) on the detuning of the trapping laser beams. n increases moderately as the detuning increases, but falls off once the detuning exceeds two linewidths. T shows a gradual dependence on δ as well.

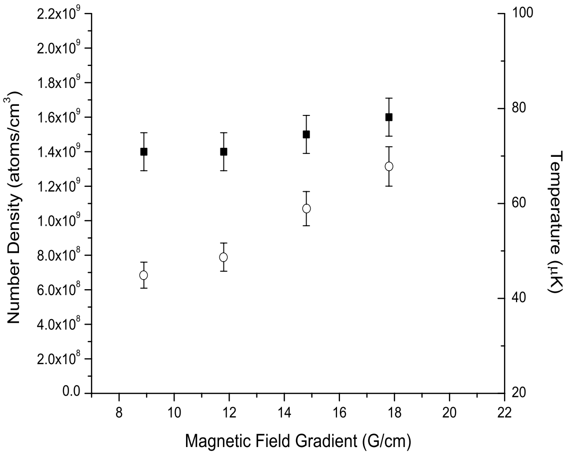

Fig. 4. Dependence of number density (filled squares) and temperature (hollow circles) on the magnetic field gradient. n and T exhibit modest changes.

as the detuning δ increases. From Eq. (1) we expect T to vary inversely with δ. Our data in Fig. 3 shows a slower decrease of T versus δ than expected, but nevertheless roughly exhibits this trend. On the other hand, the density n rises by merely a factor 2 before subsiding at the largest detuning. This is expected because, over a narrow range of detunings, increasing the detuning permits a larger velocity capture range from the background vapor. This increases the number N of atoms trapped in the same trapping volume, thus increasing the number density. However, the magnitude of the damping force falls off as the detuning increases beyond a certain value, causing an eventual decay of N and n.

In Fig. 4 we plot the effect on n and T as the magnetic field gradient is varied from 9 to 18 G/cm. We observe a moderate increase in density owing to the increase in the steepness of the trapping harmonic potential, and a rise in temperature as well.

In conclusion, we have shown that simply changing the relative intensity of the trapping laser beams enables us to vary the number density of a cold trapped atomic sample by an order of magnitude without affecting the sample temperature (Fig. 1). The temperature does not change because the total laser intensity seen by the atoms, as well as other trap parameters (laser detuning, laser beam size, and the magnetic field gradient), stay fixed. The density changes because the trap becomes anisotropic leading to changes in the volume, while the total trapped atom number stays fixed. We expect these results to be true for all typical alkali MOTs. This is because we performed auxiliary measurements of the dependence of n and T on the trap laser beam size (Fig. 2) and detuning (Fig. 3), and also the magnetic field gradient (Fig. 4). The results from these auxiliary measurements are consistent with a semi-empirical formula derived in [2] based on a widely accepted comprehensive study of alkali MOT behavior as a function of various trap parameters. The method presented in this paper, of varying n while holding T constant, is extremely useful for fundamental investigations of radiation trapping in cold dilute atomic samples [4] and of atomic transport in optical lattices [5]. Furthermore, this method may be useful in a variety of cold collision experiments where the collision cross-section is determined by mapping the trap-loss rate as a function of the trap parameters [6,7], or where cold atoms are used as targets such as in electron-impact ionization collisions [14] and ion–atom collisions [15].

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