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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]:

$$T \propto N^{1/3}/\delta. \tag{1}$$

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