Atom number in magneto-optic traps with millimeter scale laser beams

Gregory W. Hoth, Elizabeth A. Donley,* and John Kitching

National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA

**Corresponding author: elizabeth.donley@nist.gov*

Received December 26, 2012; revised January 14, 2013; accepted January 14, 2013; posted January 17, 2013 (Doc. ID 182318); published February 22, 2013

We measure the number of atoms N trapped in a conventional vapor-cell magneto-optic trap (MOT) using beams that have a diameter d in the range 1–5 mm. We show that the $N \propto d^{3.6}$ scaling law observed for larger MOTs is a robust approximation for optimized MOTs with beam diameters as small as 3 mm. For smaller beams, the description of the scaling depends on how d is defined. The most consistent picture of the scaling is obtained when d is defined as the diameter where the intensity profile of the trapping beams decreases to the saturation intensity. Using this definition, N scales as d^6 for $d < 2.3$ mm but, at larger d, N still scales as $d^{3.6}$.

OCIS codes: 020.3320, 020.7010, 130.3990.

Instruments based on laser cooled atoms have achieved extraordinary results. For example, atomic clocks can measure frequency to better than 1 part in 10^{15}, and atomic accelerometers can measure g, the local acceleration due to gravity, to 1 part in 10^8 in 1 s [1]. Typically, these instruments are table-top sized and require a carefully controlled laboratory environment to function. If these constraints could be relaxed, it would enable new applications of these precise measurements. For example, GPS receivers could incorporate miniature cold-atom clocks, and surveys of local variations in g could be done with portable cold-atom accelerometers. These applications require compact cold-atom instruments.

A fundamental limit on the performance of these devices is quantum projection noise or atom shot noise, which scales as $1/\sqrt{N}$, where N is the number of atoms interrogated [2]. To quantify how this limit will constrain the performance of a compact cold-atom sensor, it is important to estimate how N scales with the size of the device. Typically, N is limited by the equilibrium atom number of the magneto-optic trap (MOT) used to cool and collect atoms at the start of the measurement cycle.

Although many variations on the MOT have been studied over the years, we limit our attention to the standard vapor-cell MOT because it is a relatively simple and compact setup that serves as a useful baseline. A vapor-cell MOT consists of three pairs of mutually orthogonal, counterpropagating laser beams that overlap at the center of a magnetic quadrupole field inside a vacuum chamber containing a low density atomic vapor [3]. Each beam has a flat-top intensity profile with a diameter d. The trap's equilibrium atom number is given by

$$N \approx 0.1 \frac{A}{\sigma} \left(\frac{v_c}{v_t} \right)^4, \qquad (1)$$

where v_t is the average velocity of an atom in the background vapor, σ is the cross section for collisions that eject cold atoms from the trap, A is the surface area of the trapping volume, and v_c is the trap's capture velocity [4]. The beam diameter d influences the atom number through A, which scales as d^2, and through v_c, but the relationship between v_c and d is not obvious.

The capture velocity can be quantified by simulating the trajectory of an atom through the trapping region. Lindquist *et al.* studied two models for the slowing force and found that, in an optimized MOT, N scaled as $d^{3.6}$ as long as d was not too small [4]. This scaling law has been observed for MOTs with $d \sim 1$ cm [5]. For compact cold atom sensors, we are interested in the case where $d \sim 1$ mm. We have used the simple model of Lindquist *et al.* to study the relationship between N and d in this regime. This model considers a two-level atom interacting with counterpropagating plane waves in 1D. The slowing force depends on the saturation parameter, $s = I/I_{\text{sat}}$ (I is the intensity of each plane wave and I_{sat} is the saturation intensity), the optical detuning, δ, and the atom's Doppler shift, kv [4]. The capture velocity is the velocity of an atom that is just stopped after traveling a distance d. The model predicts that when d is small, N scales as d^6 and, at larger d, N approximately follows the $d^{3.6}$ scaling law.

It is difficult to specify the boundary between these two regimes in all cases, but some simple estimates can be made. The d^6 scaling regime corresponds to a slowing force that is proportional to the velocity of the atom [6]. In the two-level model, the slowing force is well approximated by $F = -\beta v$ when $|v| \le |\delta/k|$ (as long as s is not too small). This gives an estimate for the capture velocity at the transition between the scaling regimes $v_{c,t} = \delta/k$. The trap size at the transition is approximately $d_t = m v_{c,t}/\beta$ where m is the mass of the atom and β is the friction coefficient. Reasonable values of δ and s lead to an estimated transition size $d_t \approx 1 - 2$ mm. However, Pollock *et al.* [6] have observed d^6 scaling in MOTs made in microfabricated pyramids with sides as large as 7 mm. Given their results, it is not clear whether the two-level model's estimate of d_t is a reasonable approximation for ordinary vapor-cell MOTs. To determine d_t experimentally, we measured N as a function of d in a vapor-cell MOT with d between 1 and 5 mm.

^{85}Rb was trapped inside an uncoated, rectangular glass cell with a 12.5×12.5 mm cross section. The pressure inside the cell was about 10^{-8} Torr. The light source for our experiment was a 780 nm distributed Bragg reflector laser diode, frequency locked by use of saturated absorption spectroscopy. The detuning was fine-tuned by use of an acousto-optic modulator. Repump light was produced by directly modulating the laser at 2.926 GHz [7]. Typically, the repump sidebands each contained about 4% of the laser's power. The quadrupole magnetic field was produced by use of permanent magnets. The atom number was estimated by measuring the maximum fluorescence of the MOT with a calibrated photodiode. Based on the atom density typically obtained in MOTs, we estimate that the optical depth is smaller than unity for all but the largest numbers of atoms measured here. For those data, the fluorescence measurement underestimates the number of atoms by, at most, a factor of 2.

The trapping beams were produced by collimating the outputs of a 1–3 fiber splitter to make Gaussian beams with a $1/e^2$ diameter $2w_0 = 2.25$ mm. The diameter could be increased to $2w_0 = 4.5$ mm by use of beam expanding telescopes. These three beams were retroreflected to make the MOT. The size of the trapping beams was varied by use of irises placed after the fiber collimators. The minimum diameter of the irises was 1 mm. Diffraction effects significantly increase the width of an irised beam after it propagates a distance $r_{\mathrm{iris}}^2/\lambda \approx 30$ cm, which is comparable to the path length for our MOT beams. To account for the effects of diffraction, we measured the profile of the beam as a function of both the iris size and the distance from the iris by use of a CCD camera. Since these diffracted beam profiles are quite far from an ideal flat top beam, it is not obvious how to define the beam diameter d.

We explored several methods to define d based on our measurement of the diffracted beams. We defined a diameter, d_B, by calculating the size of the circle that contained 86.3% of the total power. The 86.3% cutoff was chosen so that d_B would coincide with the usual $1/e^2$ diameter when the beam was Gaussian. This definition is well suited to characterize the beam size with respect to its intensity distribution, but it does not fully take into account the spatial variation of the saturation parameter relevant for the slowing force. Therefore, we defined a second diameter d_P, by calculating the width of the beam where the intensity fell to $I = I_{\mathrm{sat}}$.

This intensity-dependent definition of d implies that the trap volume will increase with the power in the trapping beams. To test this idea, we varied the power in each beam from 1 to 4 mW while the beams were Gaussian with $2w_0 = 2.25$ mm. This corresponds to varying the average saturation parameter for each beam from 6 to 25 ($I_{\mathrm{sat}} = 3.9$ mW/cm^2). Despite these large saturation parameters, we find that N increases steadily as shown in Fig. 1. We also simulated our measurements of the atom number as a function of beam power with the stopping distance set to either d_B or d_P. Figure 1 shows that the observed increase in N can be accounted for by defining the trap size to be d_P.

We measured the atom number as a function of trap size at $\delta = 2\gamma$ and $\delta = 3\gamma$ ($\gamma = 2\pi \times 6.066$ MHz is the natural linewidth of the transition). For all the MOTs we studied, the largest number of atoms was obtained with $\delta = 2\gamma$. In both cases, we find that N is well described by a d^6 scaling law at small d and by a $d^{3.6}$ scaling law at larger d as shown in Fig. 2. For the $\delta = 3\gamma$ data, it appears that N might be falling off faster than d^6, but we

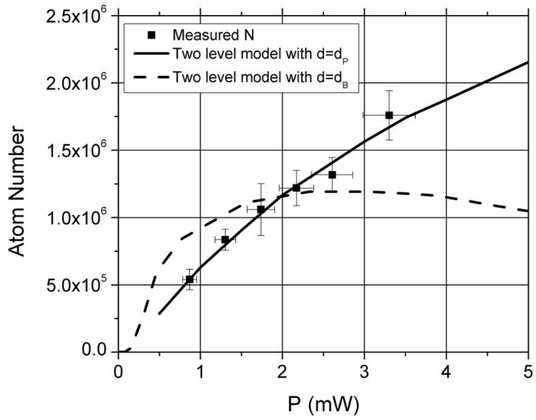

Fig. 1. Trapped atom number as a function of beam power compared to predictions of the two-level model for two definitions of d. For the dashed curve, $d = d_B = 2.25$ mm. In this case, the atom number decreases at high P because power broadening reduces the maximum slowing force. For the solid curve, $d = d_P$ for a Gaussian beam with $2w_0 = 2.25$ mm. In this case, the atom number rises with P because the size of the stopping region increases. For the simulations, $\delta = 2\gamma$ (γ is the natural linewidth) and $s = P/(\pi d^2)/I_{\mathrm{sat}}$ (the results are not sensitive to this choice for s). The simulations have been normalized to agree with the data at $P = 2$ mW. The data were taken with $\delta = 2\gamma$ and $dB/dz \approx 34$ G/cm.

attribute this to the difficulty of optimizing a MOT with a small number of atoms. Based on the fits shown in Fig. 2, the trap sizes at the transition between the scaling regimes are $d_t = 2.3 \pm 0.1$ mm and $d_t = 2.9 \pm 0.1$ mm for $\delta = 2\gamma$ and $\delta = 3\gamma$, respectively. By use of Eq. (1) with $\sigma = (3 \pm 0.5) \times 10^{-13}$ cm^2 [8], the transition capture velocities were estimated to be $v_{c,t} = 14.1 \pm 0.8$ m/s for $\delta = 2\gamma$ and $v_{c,t} = 13.9 \pm 0.7$ m/s for $\delta = 3\gamma$. For comparison, the two-level model predicts $d_t = 1$ mm, $v_{c,t} = 9.5$ m/s for $\delta = 2\gamma$ and $d_t = 2.7$ mm, $v_{c,t} = 14.2$ m/s for $\delta = 3\gamma$.

Figure 3 illustrates the scaling of N with d for optimized MOTs from 1 to 40 mm by combining our data with results from other papers cited here. The $d^{3.6}$ scaling law appears valid for a wide range of d. Figure 3 also shows how our $\delta = 2\gamma$ data appear when d_B is used to define the trap size. As long as $d > 2$ mm, both definitions of d give similar descriptions of the scaling, but they disagree at small d. Based on the evidence of Fig. 1, we believe that d_P provides a better description of the trapping volume.

The implications of these results for compact cold-atom instruments are best illustrated by an example. For a clock based on Ramsey interrogation, the quantum projection noise limit is given by $\sigma_y = (1/2\pi)(1/T_r)(1/\nu_0)\sqrt{T_c/N}$ (at 1 s of averaging) where T_r is the Ramsey period, ν_0 is the resonance frequency, T_c is the cycle period, and N is the number of atoms [2]. The stability target for the clocks in GPS-III is $\sigma_y = 6 \times 10^{-12}$ at 1 s [9]. If we assume $\nu_0 = 6.8$ GHz, $T_r = 10$ ms, and $T_c = 100$ ms, about 2×10^4 atoms are needed to push the shot noise limit below 6×10^{-12}. This small T_c can be achieved by recapturing the atoms in the MOT each cycle [10]. Based on Fig. 3, we could obtain enough atoms to achieve $\sigma_y = 6 \times 10^{-12}$ with $d = 1.5$ mm. This suggests that cold-atom devices based on compact MOTs

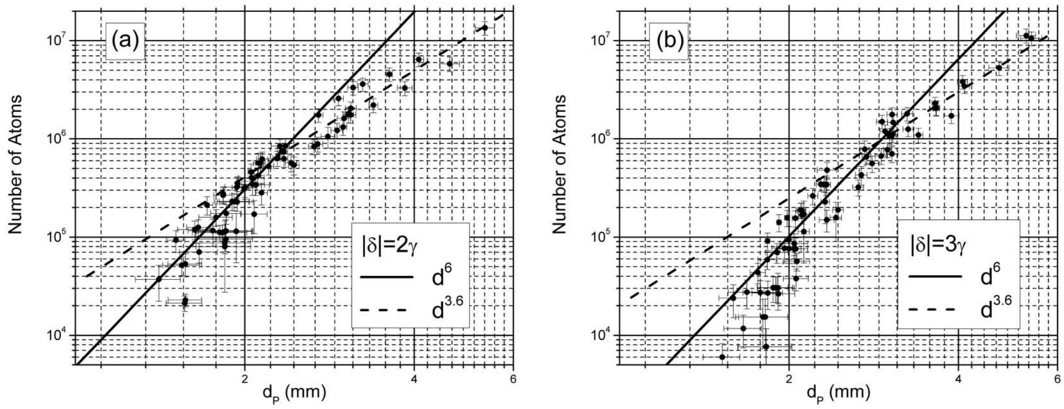

Fig. 2. Atom number as a function of effective beam diameter d_P (see text for definition) for (a) $\delta = 2\gamma$ and (b) $\delta = 3\gamma$. For all these measurements, $dB/dz \approx 34$ G/cm. The magnetic gradient was optimized for MOTs with $d_p \approx 3$ mm and $\delta = 2\gamma$, but, in practice, we found that N was not very sensitive to dB/dz. The maximum intensity and the intensity profile of the trapping beams vary significantly, but these changes are mostly accounted for by d_P. The scatter in the data is due to day to day variations in the alignment of the MOT and some intensity dependence that is not accounted for by d_P. The lines are fits to the data with the scaling exponents fixed.

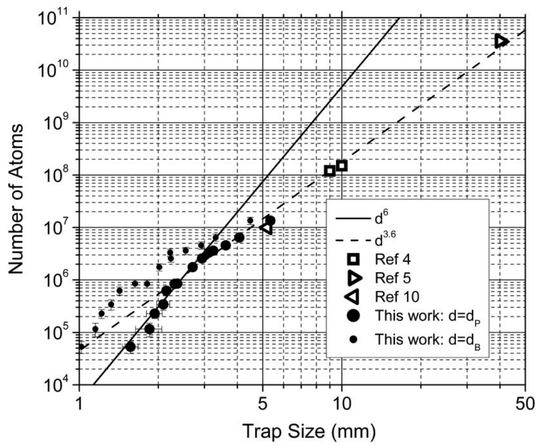

Fig. 3. Scaling of atom number with trap size illustrated with results from [4,5,10] and a subset of our $\delta = 2\gamma$ data corresponding to the highest intensities we studied. For the MOTs of [4,5,10], we define the beam size the same way as the original authors. In our data, one can see the ratio d_P/d_B is larger for the smaller beams. This is because the smaller beams are more intense.

are a realistic possibility. However, in a truly miniaturized device, the edges of the trap will be defined by the cell walls rather than the lasers, and this confined geometry may limit the number of atoms [6].

This work was funded by NIST and DARPA's Microsystems Technology Office. NIST is an agency of the US government and this work is not subject to copyright. Jennifer Sebby-Strabley is gratefully acknowledged for many useful discussions.

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