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Dark-Spot Magneto-Optical Trap of Cesium Atoms

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We constructed a dark-spot magneto-optical trap (MOT) of cesium atoms in a vapor cell. In addition to an opaque dot in the path of the repumping laser beam, we used an independent laser to optically pump the atoms into the dark hyperfine ground state. Fractional population of atoms in the bright hyperfine ground state was as low as 0.056. While the loading rate of a dark-spot MOT was only one third smaller than that of a normal MOT, its loss rate was reduced by a factor of 5, and three times more atoms were present in the dark-spot MOT. Due to the high vapor pressure in our cell, we could not observe any reduction in the density-dependent loss effect in a dark-spot MOT.

I. INTRODUCTION

Cesium is the heaviest stable alkali atom, and it plays a very important role in setting the standard for time and frequency. When the techniques for cooling and trapping atoms were developed in the 1980's, many interesting works were done with cesium atoms [1]. For example, cold and trapped samples of cesium atoms are the source for a fountain clock with its greatly improved precision [2]. Also, in precision measurements involving fundamental symmetries of physics, like parity and time reversal, the cesium atom plays a central role because violation of the symmetries is known to increase rapidly with atomic number. In addition, one of the most cited motivations for the research in the cooling and trapping of atoms has been the possibility of an improved precision measurement using cold and trapped cesium atoms [3]. Such a measurement, however, has never been realized. Finally, since the landmark experiment of rubidium Bose-Einstein condensation (BEC) in 1995 [4], there has been much effort to achieve BEC using cesium atoms, but without success so far. All of these applications of cold cesium atoms use a magneto-optical trap (MOT) as their source. It is important to have as many atoms as possible in a MOT to increase either the signal-to-noise ratio or the phase space density.

It is well known that the trapping light, which brings the atoms to a stop and lets them get trapped in a MOT in the first place, also limits the density or number of atoms in a trap via the mechanisms known as radiation trapping [5] and radiative escape [6]. The best strategy to deal with this problem is to decouple the atoms from the trapping light by turning off the hyperfine repumping light once they are slowed and trapped in a MOT. Without the repumping light, the atoms are eventually optically pumped into the lower hyperfine ground state, which does not interact with the trapping light. This idea was first successfully applied to a sodium MOT [7], and it is known as a dark-spot MOT. Since then people have applied the idea to heavier alkali atoms like rubidium [8] and cesium [9]. Construction of a dark-spot MOT for these heavier alkali atoms, however, provides a new challenge because of their larger excited-state hyperfine structures.

In the work of Ref. 8, they tried to maximize the phase-space density of cesium atoms in a dark-spot MOT. In the work reported in this article, we used basically the same idea of a dark-spot MOT, but our motivation was to maximize the number of trapped cesium atoms. We plan to use the dark-spot MOT to load cesium atoms into our newly designed optical trap. Because the loading process from the MOT to our optical trap is expected to work better when the repumping light is tuned to the D1 line, we used the D1 line in our study of the dark-spot MOT.

II. DARK SPOT MOT

In a vapor-cell MOT, cesium atoms at the low-energy tail of the Maxwell-Boltzmann distribution are constantly cooled and trapped by the light pressure regulated by a magnetic-field gradient. In a cesium MOT, the trapping light is tuned to the cycling transition from the $|6S_{1/2}, F = 4\rangle$ state to the $|6P_{3/2}, F' = 5\rangle$ state. The trapping light tuned near the cycling transition, however, can also drive the off-resonant transition to the $|6P_{3/2}, F' = 4\rangle$ state, and the atoms may fall out of the

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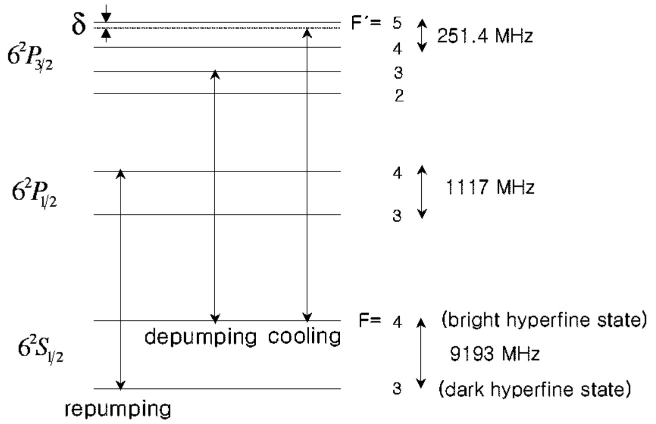

Fig. 1. Hyperfine structure of the $6S$ and the $6P$ states of cesium (not to scale).

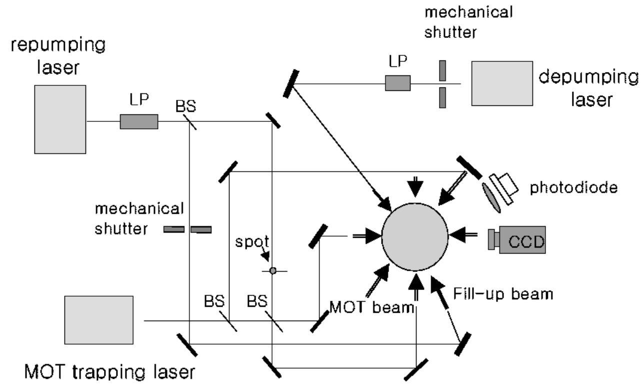

Fig. 2. Experimental setup. The dark-spot MOT is formed by blocking the center of the repumping laser with a black spot. LP is a linear polarizer, BS a beam splitter, and CCD a charge-coupled device camera.

cycle and into the lower hyperfine state $|6S_{1/2}, F = 3\rangle$. There is a hyperfine repumping light that puts the atoms in the $F = 3$ state back to the $F = 4$ state. We use the D1 transition at 895 nm from the $|6S_{1/2}, F = 3\rangle$ state to the $|6P_{1/2}, F' = 4\rangle$ state as a repumping transition. The relevant energy levels are shown in Fig. 1.

The loading rate, R, is defined as the number of atoms put into the MOT from the background vapor per unit time. Once the atoms are put into the MOT, they can escape the trap via a few processes. The simplest, and frequently the most significant, one is a collision of a trapped atom with a hot atom from the background vapor. The loss rate is proportional to the number of trapped atoms, N, and is given by $-\Gamma N$, where Γ characterizes the collision strength. Another phenomenon is known as radiative escape [6]. As the density of atoms in the trap n becomes higher collisions between trapped atoms can lead to a significant loss when one of the colliding atoms is in the excited state. The attractive force between a ground-state and an excited atoms is much larger than that of two ground-state atoms. During the lifetime of the excited state, the colliding pair can experience a large acceleration and gain enough kinetic energy to escape the trap. In addition, a photon spontaneously emitted from a trapped atom can be reabsorbed by another atom in the trap. This process is known as a radiation trapping [5]. It leads to a repulsive force between the pair of atoms and limits the maximum density attainable in a MOT. These loading and loss mechanisms can be summarized in the rate equation

$$\frac{dN}{dt} = R - \Gamma N - \beta n^2, \tag{1}$$

where β characterizes the strength of the density-dependent loss processes.

We note that the density-dependent loss processes involve a three-body collision of two atoms and one photon. We also note that even for a usual background collision, the loss rate Γ is larger when the trapped atoms are in the excited state [9]. The cross section for a trap loss collision is larger for a collision between an excited-state trapped atom and a ground-state background atom than for one between a pair of ground-state atoms. We can minimize these loss rates by keeping the trapped atoms in the lower hyperfine state ($F = 3$ for the case of cesium), which does not interact with the trapping light. We still need to keep the atoms in the higher hyperfine state ($F = 4$, bright state) while the atoms are being cooled and trapped from the vapor. This conflicting requirement can be satisfied by imaging a shadow of the repumping light onto the center of the MOT, where the atoms are already cold and trapped. This spatial separation of the bright and dark regions of a MOT leads to a greatly increased number of trapped sodium atoms in the original dark-spot MOT experiment [7]. The cesium atom has a larger excited-state hyperfine splitting, however, and the absence of repumping does not readily result in an accumulation of atoms in the dark state. We have to provide an active optical pumping into the dark state using the transition from the $|6S_{1/2}, F = 4\rangle$ state to the $|6P_{3/2}, F' = 3\rangle$ state. Such light is called a depumping beam. The combination of the shadow in the repumping and the additional depumping beam reduce the fraction of atoms in the bright state. Quantitatively, the bright fraction p is defined as

$$p = \frac{N(F=4)}{N(F=3) + N(F=4)}, \tag{2}$$

where $N(F = 3)$ and $N(F = 4)$ are the number of MOT atoms in the $6S_{1/2}, F = 3$ and $F = 4$ states, respectively.

III. EXPERIMENT

1. Experimental Apparatus

Our experimental apparatus is shown in Fig. 2. The MOT is loaded from a low-pressure cesium vapor in an

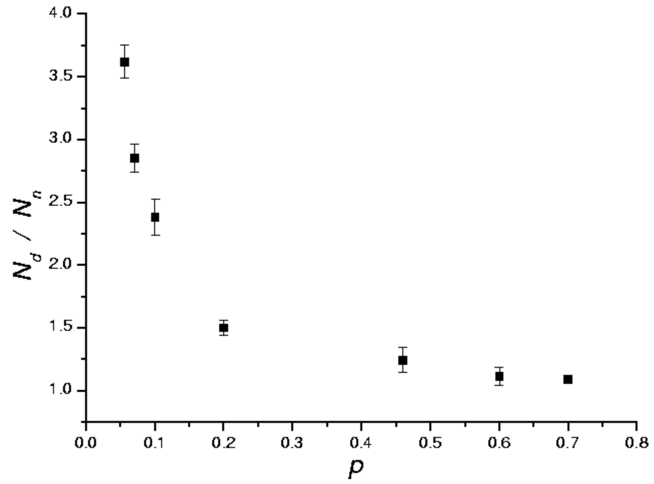

Fig. 3. Ratio N_d/N_n vs p. N_d is the number of trapped atoms in a dark-spot MOT, and N_n is the number in a normal MOT. As p becomes smaller, the ratio increases.

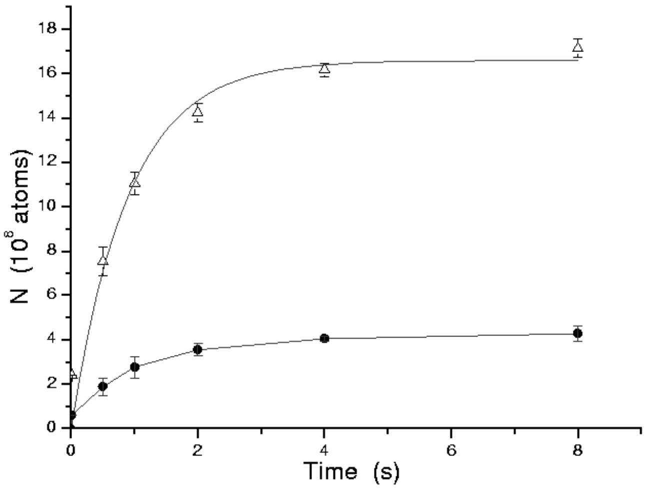

Fig. 4. Loading curves of a normal MOT (●) and a dark-spot MOT (△), when p = 0.056. The solid line shows the fitted result from the solution of Eq. (1) with $\beta = 0$.

octagonal ultrahigh-vacuum (UHV) chamber. Cesium atoms are continuously dispersed from a heated cesium getter. The background pressure without the cesium vapor in the MOT chamber is 7×10^{-10} Torr, which is obtained after a few days of operation with the cesium getter turned off and pumping with a 34-l/s ion pump. When the getter current is $3 \sim 4$ A, the pressure in the MOT chamber is $3 \times 10^{-9} \sim 8 \times 10^{-8}$ Torr. In our experiment, the cesium pressure in the MOT is 3×10^{-9} Torr, and the getter current is about 3 A. To generate the spatially varying quadrupole magnetic field, we use a pair of anti-Helmholtz coils with axes along the vertical direction. The magnetic-field gradient in our experiment is 16 G/cm in the horizontal plane. Three additional orthogonal shim coils cancel stray fields in the region of the trap, from the earth and the ion pump.

We use two external cavity diode lasers for a MOT. One is a trapping laser constructed with 100-mW laser diode. The frequency of the trapping laser is tuned to the 13-MHz below the $6S_{1/2}, F = 4 \rightarrow 6P_{3/2}, F' = 5$ resonance and stabilized using the signal from a saturated-absorption spectrometer. The size of the trapping laser is expanded to 5.2 mm (e^{-2} intensity radius) and split into three circularly polarized beams of 9-mW each. The other laser is for the hyperfine repumping which pumps atoms in $F = 3$ back into $F = 4$. The repumping laser is also constructed with a laser diode. We use the $6S_{1/2}, F = 3 \rightarrow 6P_{1/2}, F' = 4$ transition for repumping. The repumping laser is also expanded to a similar spot size as the trapping laser and overlapped with the trapping laser in the horizontal plane.

The dark-spot MOT is formed by blocking the center of the repumping laser beam with a black spot. The spot is a square (3 mm × 3 mm). We use a small fraction of the repumping laser beam to illuminate the dark center of the MOT. It allows us to convert the dark-spot MOT back to a normal one. We call the beam which fills the dark region a "fill-up" beam and switch it on and off with a shutter (see Fig. 2). For heavy alkali atoms like cesium, the hyperfine splitting between $6P_{3/2}, F' = 4$ and $6P_{3/2}, F' = 5$ is so large (254 MHz in cesium atoms in comparison with 84 MHz in sodium atoms) that the number of atoms which decay into $F = 3$ out of the cycling transition is very small. This is a serious problem in the dark-spot MOT because we intend to populate the atoms in the trap center into $F = 3$. To solve this problem when constructing the dark-spot MOT for the cesium atoms, we add one more laser that sends atoms intentionally into $F = 3$. We call it a "depumping" laser. The frequency of the depumping laser is locked to the peak of the $6S_{1/2}, F = 4 \rightarrow 6P_{3/2}, F' = 3$ transition. The atoms excited to $F' = 3$ can decay back to $F = 3$. The spot size of the depumping laser is 1.9 mm. Its maximum power is 2.5 mW, and the depumping laser shines on the dark region through a small window in the octagonal UHV chamber (see Fig. 2). The depumping laser beam is linearly polarized. We control its intensity by using a linear polarizer and switch the depumping beam off completely with a shutter.

We measure the number of trapped atoms in the dark-spot MOT by detecting the fluorescence of the cloud using a photodiode. In our experiment, we measure the loading rate, the number, and the lifetime of the trapped atoms while we change p in the dark-spot MOT.

2. Measurements

The important parameter in the dark-spot MOT is p. The definition of p is given in Eq. (2), and the value of p is close to 1 in a normal MOT. In our experiment,

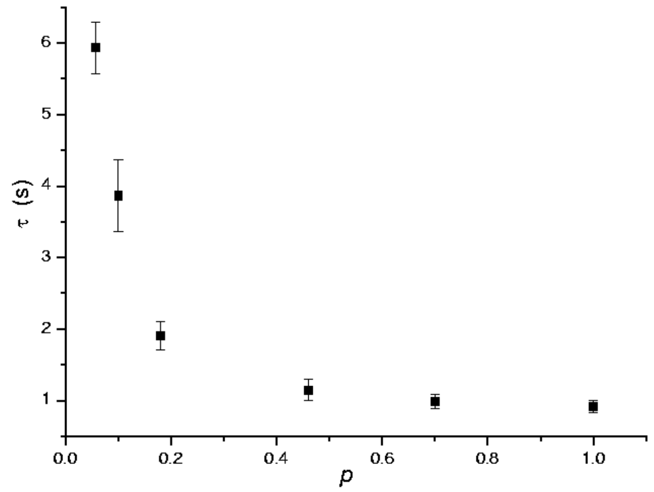

Fig. 5. Lifetime τ vs p. τ is related to the loss rate Γ through the relation $\tau = 1/\Gamma$. In a normal MOT, $\tau = 0.91$ s while in a dark-spot MOT with $p = 0.056$, it is $\tau = 5.9$ s. τ is obtained from the fitted loading curve.

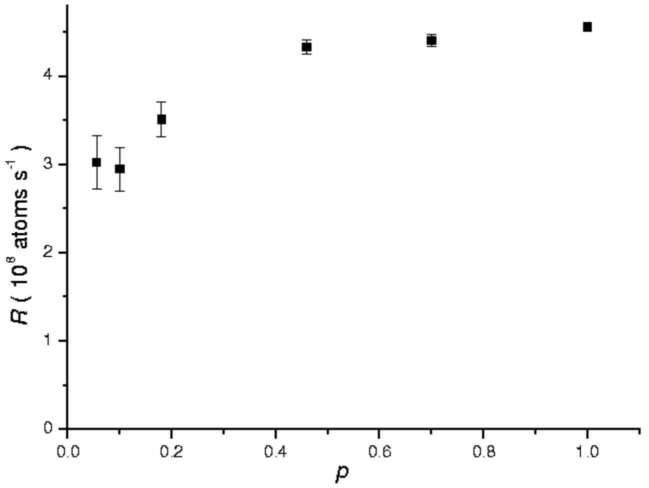

Fig. 6. Loading rate R in the dark-spot MOT vs p. The loading rate in a normal MOT is 4.4×10^8 atoms s^{-1}. R is obtained from the slope of the fitted loading curve at the beginning of the loading.

we can reduce it by controlling the depumping laser intensity and the repumping laser frequency. When the depumping laser beam is blocked and the frequency of the repumping laser is tuned near the $F = 3$ to $F' = 4$ transition, p is 0.67 even with a dark spot on the repumping beam. However, when we shine the depumping laser on the dark region and increase its intensity, we find that p is reduced. p is also closely related to the beam size and the frequency, as well as to the intensity of the depumping laser. The frequency of the depumping laser is locked to the peak of the $F = 4$ to $F' = 3$ transition, and its spot size is 1.9 mm. Under this condition, we can reduce p to as low as 0.15. When the frequency of the repumping laser is near the resonance, a stray repumping laser, which scatters into the dark region, keeps us from obtaining a p lower than 0.15. We can obtain the minimum value of p, 0.056, only by increasing the repumping laser detuning to 18 MHz. Under the optimum condition of the depumping laser and the repumping laser, we can vary p continuously from 0.67 to 0.056 by increasing the intensity of the depumping laser.

We measure p as follows: First, we load the dark-spot MOT for some time while the fill-up beam is turned off and the depumping beam is switched on, and we measure the fluorescence signal with the fill-up beam and the depumping beam turned off. In this case, the fluorescence is proportional to the population of atoms in the bright hyperfine state. Secondly, in the same condition, we load the dark-spot MOT. This time, however, the depumping laser is turned off and the fill-up beam is switched on, and then the fluorescence signal is measured. In this process, most of the atoms populate the bright hyperfine state due to the fill-up beam. We obtain the value of p by dividing the fluorescence signal from the first measurement by that from the second one.

We measure the number of trapped atoms, the lifetime τ ($\tau = 1/\Gamma$), and the loading rate R while changing p. We also study the density-dependent loss β. Figure 3 shows the ratio of the trapped atoms for a dark-spot MOT to that for a normal MOT as p is changed. We measure the number of trapped atoms from the fluorescence signal. Under a bench-mark condition, the number of trapped atoms in the normal MOT is 4×10^8 [10]. In this set of measurements, we first load a normal MOT for a time longer than τ and detect its fluorescence signal. Next, we form a dark-spot MOT and load for the same period as in the case of the normal MOT. At the end of the loading period, we turn off the depumping beam, turn on the fill-up beam, and then detect the fluorescence signal. By comparing the fluorescence signals from the two measurements, we study whether the dark-spot MOT traps more atoms than the normal MOT. Finally, we measure the value of p as described above. From Fig. 3, we find that as p becomes smaller, the number of trapped atoms in the dark-spot MOT increases by as much as a factor of 3.

Figure 4 presents the loading curves of both a normal and a dark-spot MOT when $p = 0.056$. At same time and under same conditions, we must measure the fluorescence to compare the normal MOT with the dark-spot MOT. Thus, the data points of Fig. 4 are obtained by doing destructive measurements. The solid line of Fig. 4 shows the fitted result from the solution of Eq. (1) without β. When we fit the measured data to the loading curves by using the solution of Eq. (1) with $\beta = 0$, we obtain the lifetime and the loading rate. Figure 5 and 6 represent these results. Figure 5 shows the variation of τ with p. The lifetime τ is defined as $\tau = 1/\Gamma$, and Γ is the loss rate from the collision with background atoms. It has been pointed out [8] that the collisional loss rate is smaller when the trapped atom is in the dark hyperfine state than when it is in the bright hyperfine state, so we reduce the background collisional loss by confining trapped atoms into the dark hyperfine state. From Fig. 5, we also find that as p becomes smaller, τ can be increased by as much as 5 times. Figure 6 presents the variation of the loading rate R with p. The loading rate is obtained from the slope of the loading curve at the beginning of the loading. The dark-spot MOT does not help the loading process, and R in the dark-spot MOT cannot be larger than that of the normal MOT. The loading rate of the normal MOT is 4.4×10^8 (atoms s^{-1}). As shown in Fig. 6, R tends to decrease as p decreases, but even when $p = 0.056$, R_d is still 67 % of R_n (R_d is the loading rate in a dark-spot MOT, R_n is the loading rate in a normal MOT).

Fitting of the observed loading curve with the solution $N(t) = R/\Gamma(1 - e^{-\Gamma t})$ of Eq. (1) with $\beta = 0$ produces good agreement within the measurement error, which implies that, in our experimental situation, the density-dependent loss β does not play an important role. The operating vapor pressure, and consequently the background collision rate Γ is too large and dominating for the density-dependent effect to become important. Anderson *et al.* reported a significant reduction in β in their rubidium dark-spot MOT when the vapor pressure was as low as 10^{-11} Torr [8].

IV. CONCLUSION

We studied a dark-spot MOT of cesium atoms by having a dark spot on the repumping beam and a separate depumping beam. We found that the background loss rate Γ decreased while the loading rate more or less remained constant and obtained a fivefold increase in the number of trapped atoms. However, the vapor pressure of our cell was too high for us to observe a reduction in the density-dependent loss effect. We plan to use an increased number of atoms trapped in a dark-spot MOT for our study of a novel cesium optical trap.

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