Investigation of ultracold atoms and molecules in a dark magneto-optical trap*

Wang Li-Rong(汪丽蓉)†, Ji Zhong-Hua(姬中华), Yuan Jin-Peng(元晋鹏), Yang Yan(杨 艳), Zhao Yan-Ting(赵延霆), Ma Jie(马 杰), Xiao Lian-Tuan(肖连团), and Jia Suo-Tang(贾锁堂)

State Key Laboratory of Quantum Optics and Quantum Optics Devices, Laser Spectroscopy Laboratory, Shanxi University, Taiyuan 030006, *China*

(Received 20 March 2012; revised manuscript received 23 May 2012)

In this paper, ultracold atoms and molecules in a dark magneto-optical trap (MOT) are studied via depumping the cesium cold atoms into the dark hyperfine ground state. The collision rate is reduced to 0.45 s^{-1} and the density of the atoms is increased to 5.6×10^{11} cm^{-3} when the fractional population of the atoms in the bright hyperfine ground state is as low as 0.15. The vibrational spectra of the ultracold cesium molecules are also studied in a standard MOT and in a dark MOT separately. The experimental results are analyzed by using the perturbative quantum approach.

Keywords: cold atom, dark magneto-optical trap, photoassociation

PACS: 34.50.Cx, 37.10.Gh, 33.15.Mt, 33.80.–b **DOI:** 10.1088/1674-1056/21/11/113402

1. Introduction

Laser cooling of neutral atoms in a magneto-optical trap (MOT) is an important tool in modern atomic physics. Ultracold atoms have received increasing attention due to their significant advances and potential applications, such as atomic spectroscopy of cold atoms,[1,2] ultracold molecules,[3,4] new frequency standards, precision measurements, quantum information devices,[5–7] and the Bose–Einstein condensation in a dilute atomic vapor.[8]

In the experiments with MOT, such as precision spectroscopy and the Bose-Einstein condensation, it is important to reduce the inelastic collision rate while increase the cold atom density. The dark MOT becomes a useful tool, since it avoids unwanted scattering effects by shelving the atoms into a dark hyperfine state and reducing the time spent in their cooling cycle. Ketterle *et al.* first proposed a dark MOT to confine atoms predominantly in a dark hyperfine level, it was shown that more than 10^{10} sodium atoms were confined in the MOT.[9] The dark trap was also used to suppress the light-assisted collisional loss from a low-pressure ^{87}Rb vapor-cell trap and obtain a large fractional population in the lower hyperfine ground state about 5×10^7 trapped atoms.[10] In 2008, the lifetime of rubidium atoms was measured in a dark MOT.[11] Recently, a study of loading Rb atoms into a dark MOT by controlling the current through a getter source was reported,[12] the maximum collection rate 3.6×10^7 atom/s and the background atom collision rate 1.9 s^{-1} were obtained.

In this paper, a density of nearly 5.6×10^{11} cm^{-3} is achieved for trapped cesium atoms confined in a dark MOT by directing most of the population to a hyperfine level which does not interact with the trapping laser. The collision rate is reduced by a factor of 2. The high resolution photoassociation vibrational spectroscopy of cesium molecules by using the usual trap loss method is also studied in this dark MOT. Compared to the standard MOT, the signal-to-noise ratio is increased prominently.

2. Relevant energy levels and experimental setup

The relevant energy levels in the D_2 resonance line of cesium are depicted in Fig. 1, where T, R, and D represent trapping, repumping, and depumping lasers,

*Project supported by the National Basic Research Program of China (Grant No. 2012CB921603), the International Science & Technology Cooperation Program of China (Grant No. 2011DFA12490), the National Natural Science Foundation of China (Grant Nos. 10934004, 60978001, 60978018, 60808009, 61078001, and 61008012), and the Natural Science Foundation of Shanxi Province, China (Grant No. 2011011004).

†Corresponding author. E-mail: wlr@sxu.edu.cn

© 2012 Chinese Physical Society and IOP Publishing Ltd

respectively. The frequency of the trapping laser is red detuned from the $6S_{1/2}F = 4 \rightarrow 6P_{3/2}F' = 5$ atomic transition by about 12.5 MHz. The repumping laser frequency is locked to the transition $6S_{1/2}$ $F = 3 \rightarrow 6P_{3/2}F' = 4$, it is used to pump the population in the $6S_{1/2}F = 3$ level back to the $6S_{1/2}F = 4$ level. The depumping beam frequency is resonant with the transition $6S_{1/2}F = 4 \rightarrow 6P_{3/2}F' = 4$. In this experiment, $6S_{1/2}F = 3$ is the dark state, while $6S_{1/2}F = 4$ is the bright state.

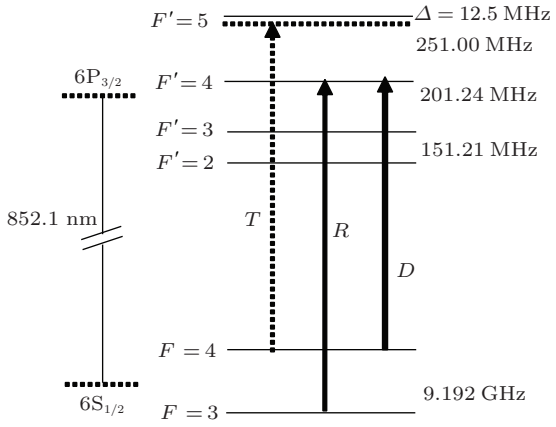


Fig. 1. Relevant energy levels in the D_2 resonance line of cesium, where T, R, and D are trapping, repumping, and depumping lasers, respectively.

The experimental setup is similar to that in Ref. [13]. The MOT is produced in a stainless-steel chamber with a vacuum environment about 1.6×10^{-7} Pa. A pair of anti-Helmholtz configuration current-carrying coils generate a 15-G/cm magnetic gradient along the axis of the coils, and three pairs of coils are placed around the chamber in order to compensate for the geomagnetism at the site of the cold atom cloud. The frequencies of the two external cavity diode lasers (Toptica DL100) are locked by saturation absorption spectroscopy to provide trapping and repumping beams. Both of the trapping and the repumping beams are expanded to about 15 mm in diameter. The power of the trapping beam is about 15 mW. An acousto-optic modulator is used to adjust the trapping laser frequency, which is tuned 12.5 MHz below the ^{133}Cs $6S_{1/2}F = 4 \rightarrow 6P_{3/2}F' = 5$ hyperfine level transition. The power of the repumping beam is 5 mW, and its frequency is locked to the transition $6S_{1/2}F = 3 \rightarrow 6P_{3/2}F' = 4$.

In order to build a dark MOT,[14] a depumping beam is generated from the trapping laser by passing through another acousto-optic modulator, which adjusts the frequency to the ^{133}Cs $6S_{1/2}F = 4 \rightarrow 6P_{3/2}F' = 4$ hyperfine level transition. The power of the depumping beam is about 40 μW, and its diameter is 3 mm. The depumping and the repumping beams are combined using a polarizing beam splitter. In order to produce cesium atoms in the dark state ($6S_{1/2}F = 3$), a black dot with 5 mm in diameter is placed in the center of repumping with the depumping beam in the black hole. The combined beam passes through a pair of lenses ($f = 20$ cm) and is injected into the vacuum chamber to eliminate the Fresnel diffraction. A charge-coupled device (CCD) camera is used to measure the dimension of the cold atoms. The dimension of the cold atoms is about 400 μm. We can trap about 3.0×10^8 cold atoms at a density of 5.6×10^{11} cm^{-3}. The temperature of the cold atoms is measured to be about 100 μK by the time of flight absorption imaging.

The photoassociation laser is provided by a continue-wave (cw) tunable Ti:sapphire laser system (MBR110) with a linewidth less than 100 kHz and an output power of 600 mW. The frequency of the photoassociation laser is monitored by a wavelength meter (WS/7R) with an accuracy of 60 MHz. The photoassociation laser is focused into the center of the dark MOT with a diameter of 500 μm, resulting in an available intensity up to 300 W/cm^2. The fluorescence yielded from the trapped cold atoms is collected by a convex lens and is detected by an avalanche photodiode (Si APD).

3. Experimental results and analysis

The success of trapping atoms in a dark MOT is determined by whether there is a high fractional population in the dark state. The parameter P is used to denote the fraction of atoms in the bright state ($6S_{1/2}F = 4$) in the dark MOT[9]

$$P = \frac{N_{F=4}}{N_{F=4} + N_{F=3}}, \tag{1}$$

where $N_{F=4}$ and $N_{F=3}$ are the cesium atom numbers in the $6S_{1/2}F = 4$ and the $6S_{1/2}F = 3$ states, respectively.

The relation between the cold atom fluorescence and the cold atom number can be expressed as[15]

$$\frac{f}{N} = \frac{1}{2\tau} \frac{G\Omega_0^2/2}{(\omega_0 - \omega)^2 + (\Gamma/2)^2 + (\Omega_0^2/2)}, \tag{2}$$

where G is the photon collection efficiency, N is the total number of cold atoms in the trap, τ, Γ, and Ω_0 are the radiative lifetime, the natural linewidth, and the resonant Rabi frequency, respectively. In this experiment, the parameter P is obtained by measuring the cold atom fluorescence. The measurement of parameter P consists of two steps. Firstly, as showed in Fig. 2, we load the dark MOT, while the fill-in laser (a fraction of the repumping laser before the glass plate with a dark spot[12]) is switched off, and the depumping laser is turned on, the fluorescence of cold atoms is measured, which is proportional to the population of cold atoms in the bright hyperfine state. The fluorescence intensity is low, because most atoms are populated in the dark state ($6S_{1/2}F = 3$). Secondly, the depumping laser is turned off, and the fill-in laser is turned on, the fluorescence signal is measured again. In this process, most cold atoms are trapped into the bright hyperfine state due to the fill-in laser. The value of parameter P is obtained by dividing the fluorescence signal obtained from the first measurement by that from the second measurement. The parameter P varies in the range of 0.15–1 by appropriately changing the intensity of the depumping laser.

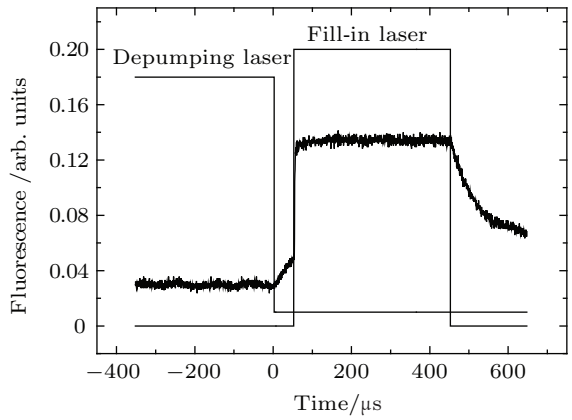


Fig. 2. Fluorescence variation of cesium atoms.

In general, collisions in traps are investigated by either detecting the product resulting from the binary encounter or through the loss of the colliding species from the trap. When an ultracold collision releases kinetic energy, the reaction rate can be measured by observing the time dependence of the number of cold atoms N. The rate equation for number N of the trapped atoms is given by[16]

$$\frac{\mathrm{d}N}{\mathrm{d}t} = L - \gamma N - \beta \int_v n^2(r,t)\,\mathrm{d}^3 r, \qquad (3)$$

where L is the capture rate, γ is the rate constant for the collisions of trapped atoms with the thermal background gas, and β is the loss-rate constant due to the collisions between trapped atoms.

The loading curve in the standard MOT and that in the dark MOT under the same conditions ($P = 0.22$) are shown in the Fig. 3. The number of cold atoms is obtained using the fluorescence measurement. The data points are the experimental results, while the solid curves are the fitting curves according to Eq. (1) without loss-rate constant β. The β is neglected, because the background collision γN is larger than the collisions between trapped atoms $\beta \int_v n^2(r,t)\,\mathrm{d}^3 r$. It can be seen that the experimental results agree well with the theoretical calculations. The loading rate in the standard MOT is 3.5×10^8 atom$\cdot$s^{-1}, while that in the dark MOT is 1.6×10^8 atom$\cdot$s^{-1}. The loading rate is obtained from the slope of the fitting curve at the beginning of the loading when the background collision can be neglected.

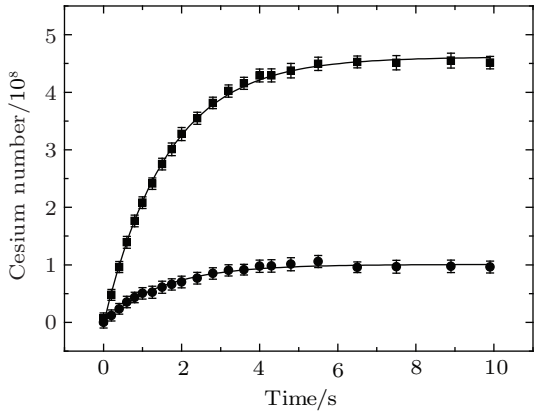


Fig. 3. Time dependences of cesium atom numbers in the standard MOT (circle) and in the dark MOT (square), where $P = 0.22$.

Figure 4 shows the cold atom densities and the collision loss rates with the background atoms for different P. The γ is obtained from the loading curve. The cold atom density in the dark MOT increases from 0.42×10^{11} cm^{-3} to 5.6×10^{11} cm^{-3} when P varies from 1 to 0.15. At the same time, the collision loss rate decreases from 0.94 s^{-1} to 0.45 s^{-1}. In the dark MOT, most of the trapped atoms are in the dark state, which do not take part in the cooling cycle. So the collision rate reduces, and the cold atom density increases compared to that in the standard MOT.

The photoassociation of cold atoms is also studied in the dark MOT. This technique probes the free-bound transition (from free atoms to a bound

molecule) with a higher resolution. In this experiment, the frequency of the photoassociation laser is red tuned to be about 51 cm^{-1} below the $6P_{3/2}+6S_{1/2}$ dissociation limit. The rotationally resolved trap-loss spectra for low-lying vibrational level $\upsilon = 17$ of cesium molecule of the 0_g^- pure long-range state are shown in Fig. 5. The photoassociation laser is scanned from 11681.31 cm^{-1} to 11681.40 cm^{-1}. The scan rate is 50 MHz/s. The upper spectroscopy is measured in a standard MOT. Rotational progressions are observed for each vibrational quantum number up to $J = 6$. For the 0_g^- long-range state, the vibrational features ($J = 0$, 2) are associated with angular momentum quantum number $l = 0$ scattering, while the vibrational features for $J = 1$, 3 are associated with angular momentum quantum number $l = 1$. The vibrational features for $J \geq 4$ can come from angular momentum quantum number $l \geq 2$. This is due to the fact that for the standard MOT, the trapping laser is left on during the photoassociation process, leading to an acceleration of the colliding pair at long range and thus to an increased number of observed partial waves.[17]

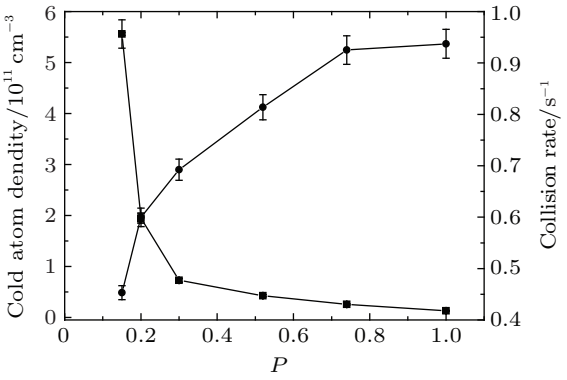


Fig. 4. Cold atom density (square) and collision rate (circle) each as a function of P in the dark MOT.

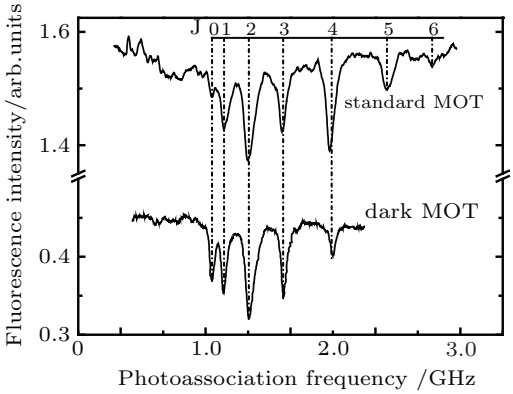


Fig. 5. Trap loss spectra of cesium atoms (low-lying vibrational level $\upsilon = 17$ of 0_g^- pure long-range state) in the standard MOT and in the dark MOT. The spectrum in the dark MOT is shifted by 18.4 GHz in order to compare with that in the standard MOT.

The trap-loss spectroscopy below is obtained in the dark MOT. Most of cold atoms are in the dark state ($6S_{1/2}F = 3$). The photoassiation frequency is shifted by 18.4 GHz, which is two times of the hyperfine structure energy of the cesium atom (9.19 GHz). Thus the spectroscopy also shifts 18.4 GHz compared with that in the standard MOT. The photoassication rate in the dark MOT is larger than that in the standard MOT. Rotational progressions are observed for rotational quantum numbers up to $J = 4$.

The results can be analyzed qualitatively by using the perturbative quantum approach.[18] The photoassociation progress of cesium atoms can be expressed as

$$\begin{aligned} &\mathrm{Cs(6s)} + \mathrm{Cs(6s)} + \hbar(\omega_0 - \delta_\mathrm{L}) \\ &\rightarrow \mathrm{Cs}_2^*(\Omega_{\mathrm{u,g}}(6\mathrm{s}+6\mathrm{p},\ {}^2\mathrm{P}_{3/2}); \upsilon, J). \end{aligned} \tag{4}$$

The formation rate of molecules in the $J_n = 0$ level is

$$\begin{aligned} R_n = \frac{N}{V}\left[\frac{\pi^2}{2}\hbar^2\left(\frac{1}{2\pi\mu k_\mathrm{B}T}\right)^{3/2}\right] E_0^2 \left|\langle ns|\, ez\, |np\rangle\right|^2 \\ \times\ \mathrm{e}^{-\beta E_r}\frac{\sin^2[k_r(R_0^n - A(k)]}{(3E_r\hbar\Delta_n)^{1/2}}. \end{aligned} \tag{5}$$

For the other transitions $J_n \neq 0$, we have

$$\begin{aligned} R_n = (2l+1)\frac{N}{V}\left[\frac{\pi^2}{2}\hbar^2\left(\frac{1}{2\pi\mu k_\mathrm{B}T}\right)^{3/2}\right] \\ \times E_0^2 \left|\langle ns|\, ez\, |np\rangle\right|^2 \mathrm{e}^{-\beta E_r}\left[\frac{2\mu(R_0^n)^2}{3\hbar^3\Delta_n}\right]^{1/2} \\ \times J_{l+1/2}^2(k_r R_0^n), \end{aligned} \tag{6}$$

where N/V is the cold atom density, and T is the cold atom temperature. From Eqs. (5) and (6), we find that the formation rate of molecules is proportional to the cold atom density. The formation rate of molecules increases with the decreasing cold atom temperature. The theoretical conclusions agree well with the experimental results. As the results discussed in this paper, the atomic density increases and the collision rate decreases in the dark MOT compared to those in the standard MOT. The cold atom temperature will be decreased because the collision rate decreases. The photoassication rate in the dark MOT is larger than that in the standard MOT. Rotational progressions are observed for each vibrational quantum number up to $J = 4$ in the dark MOT, which is less than that in the standard MOT. As mentioned above, it is due to the acceleration effect of the trapping laser in the standard MOT.

4. Conclusion

In conclusion, a dark MOT has been studied, which confines cesium atoms predominantly in the dark hyperfine ground state. In this way, limitations of the standard magneto-optical trap can be overcome, and a density closes to 5.6×10^{11} cm^{-3} with more than 10^8 trapped atoms have been achieved. The high cold atom density and the low collision rate obtained in the cesium dark MOT have been used to increase the formation rate of the ultracold molecules. In the future, we will study the formation and the interaction of RbCs molecules in a double dark MOT.

References

[1] Jiang K J, Li K, Wang J and Zhan M S 2006 *Acta Phys. Sin.* **55** 125 (in Chinese)

[2] Qiu Y, He J, Wang Y H, Wang J, Zhang T C and Wang J M 2008 *Acta Phys. Sin.* **57** 6227 (in Chinese)

[3] Wu J Z, Jie M, Zhang Y C, Li Y Q, Wang L R, Zhao Y T, Chen G, Xiao L T and Jia S T 2011 *Phys. Chem. Chem. Phys.* **13** 18921

[4] Zhang H S, Ji Z H, Yuan J P, Zhao Y T, Ma J, Wang L R, Xiao L T and Jia S T 2011 *Chin. Phys.* B **20** 123702

[5] Ke M, Yan B, Cheng F and Wang Y Z 2009 *Chin. Phys.* B **18** 4823

[6] Hudson J J, Tarbutt M R and Hinds E A2002 *Phys. Rev. Lett.* **88** 067901

[7] Rabl P, DeMille D, Doyle J M, Lukin M D, Schoelkopf R J and Zoller P 2006 *Phys. Rev. Lett.* **97** 033003

[8] Burovski E, Kozik E, Prokof'ev N, Svistunov B and Troyer M 2008 *Phys. Rev. Lett.* **101** 090402

[9] Ketterle W, Davis K B, Joffe M A, Martin A and Partchard D 1993 *Phys. Rev. Lett.* **70** 2253

[10] Anderson M H, Petrich W, Ensher J R and Cornell E A 1994 *Phys. Rev.* A **50** R3597

[11] Permyakova O I, Yakovlev A V and Chapovsky P L 2008 *Quantum Electronics* **38** 884

[12] Singh S, Tiwari V B and Rawat H S 2010 *Journal of Experimental and Theoretical Physics* **111** 371

[13] Wang L R, Ma J, Zhang L J Xiao L T and Jia S T 2006 *Acta Phys. Sin.* **15** 1268 (in Chinese)

[14] JI Z H, Zhang H S, Wu J Z, Yuan J P, Zhao Y T, Ma J, Wang L R, Xiao L T and Jia S T 2010 *Chin. Phys. Lett.* **28** 08371

[15] Marcassa L, Bagnato V, Wang Y, Tsao C and Weiner J 1993 *Phys. Rev.* A **47** R4563

[16] Monroe C, Swann W, Robinson H and Wieman C 1990 *Phys. Rev. Lett.* **65** 1571

[17] Lignier H, Fioretti A, Horchani R, Drag C, Bouloufa N, Alliegrini M, Dulieu O, Pruvost L, Pillet P and Comparat D 2011 *Phys. Chem. Chem. Phys.* **13** 18910

[18] Pillet P, Crubellier A, Bleton A, Dulieu O, Nosbaum P and Masnou-Seeuws F 1997 *J. Phys.* B: *At. Mol. Opt. Phys.* **30** 2801