Systematically investigating the polarization gradient cooling in an optical molasses of ultracold cesium atoms*

Ji Zhong-Hua(姬中华), Yuan Jin-Peng(元晋鹏), Zhao Yan-Ting(赵延霆)†,
Chang Xue-Fang(常雪芳), Xiao Lian-Tuan(肖连团), and Jia Suo-Tang(贾锁堂)

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

(Received 12 March 2014; revised manuscript received 11 May 2014; published online 10 September 2014)

We systematically investigate the polarization gradient cooling (PGC) process in an optical molasses of ultracold cesium atoms. The SR mode for changing the cooling laser, which means that the cooling laser frequency is stepped to the setting value while its intensity is ramped, is found to be the best for the PGC, compared with other modes studied. We verify that the heating effect of the cold atoms, which appears when the cooling laser intensity is lower than the saturation intensity, arises from insufficient polarization gradient cooling. Finally, an exponential decay function with a statistical explanation is introduced to explain the dependence of the cold atom temperature on the PGC interaction time.

Keywords: ultracold atoms, optical molasses, polarization gradient cooling

PACS: 37.10.De, 67.85.–d, 37.10.Vz **DOI:** 10.1088/1674-1056/23/11/113702

1. Introduction

With the development of laser cooling and trapping of neutral atoms, ultracold atoms have received increasing attention due to their significance and potential applications, such as in time and frequency standard,[1] atom interferometry,[2] Bose–Einstein condensation,[3] atom laser,[4] ultracold molecules,[5] and quantum information.[6] The sub-Doppler cooling mechanism is the foundation of the above mentioned applications. So many cooling methods are introduced to achieve sub-Doppler cooling cold atoms, such as optical molasses,[7] Raman cooling,[8] velocity-selective coherent population trapping,[9] and evaporative cooling.[10] Among those methods, the optical molasses is widely used for its simplicity and effectiveness. The polarization gradient cooling (PGC) mechanism of cold atoms was very early proposed by the Cohen-Tannoudji group[11] and Chu group.[12,13] Later, the method was expanded to gray optical molasses,[14] optical lattices,[15] and even the gray optical lattice.[16] Recent experiments showed that the PGC can also work well even for the small hyperfine splitting atoms.[17]

According to the theory of polarization gradient cooling, the equilibrium temperature T_e of cold atoms is given by

$$T_e \approx C\hbar\Omega^2/k_B|\delta|, \tag{1}$$

where C is a numerical factor on the order of 0.1, k_B is the Boltzmann constant, $\hbar$ is the reduced Planck constant, $\delta = \omega_L - \omega_A$ is the laser detuning of the incident laser frequency ω_L from the atom resonance frequency ω_A, and $\Omega = \boldsymbol{d}\cdot\boldsymbol{E}/\hbar$ is the Rabi frequency describing the coupling between the atom dipole moment $\boldsymbol{d}$ and the electric field vector $\boldsymbol{E}$. This equation means that the cold atom temperature is proportional to the cooling laser intensity at a given detuning and inversely proportional to the cooling laser detuning at a given intensity.

Some researchers have investigated the dependences of the cold atom temperature on the laser intensity and the detuning. For example, Salomon *et al.* found that the temperature of cold cesium atoms depends on the cooling laser intensity-to-detuning ratio.[18] Wang *et al.* measured the dependence on the cooling laser intensity and the detuning for ^{87}Rb atoms.[19] Hou *et al.* also studied the relationship between the temperature of cold atoms and the cooling laser intensity-to-detuning ratio.[20] An easy method to tune the cooling laser frequency was also presented.[21] However, there are few reports systematically investigating the influence of the experimental parameters in the PGC process on the cold atom temperature.

Ultracold cesium atoms, due to their simple structure, available commercial laser, and importance in the atom clock, are widely investigated all over the world. In this paper, we systematically investigate the process of polarization gradient cooling in the optical molasses of cold cesium atoms. We investigate the dependence of the temperature of the cold cesium atoms on some important experimental parameters, which include the changing modes, the cooling laser detuning and intensity, and the PGC interaction time. Theoretical explanation, experimental verification, and mathematical simulation are in-

*Project supported by the National Basic Research Program of China (Grant Nos. 2012CB921603 and 2010CB923103), the International Science & Technology Cooperation Program of China (Grant No. 2011DFA12490), the National Natural Science Foundation of China (Grant Nos. 11304189, 61378015, and 61275209), the Project for Excellent Research Team of the National Natural Science Foundation of China (Grant No. 61121064), the Program for Changjiang Scholars, China, and the Innovative Research Team in University, China (Grant No. IRT13076).

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

© 2014 Chinese Physical Society and IOP Publishing Ltd

troduced to analyze the experimental results.

2. Experimental setup and timing sequence

Our experiment starts with a standard vapor-loaded ^{133}Cs magneto-optical trap (MOT) in a commercially available stainless steel chamber, which is slightly modified from the system used before.[22] The background pressure is usually about 5×10^{-7} Pa when the atom vapors fill the vacuum chamber. A pair of coils with the anti-Helmholtz configuration generates a magnetic field gradient of about 12 G/cm. Three pairs of coils with the Helmholtz configuration are placed around the vacuum chamber to compensate geomagnetism at the position of the cold atom clouds. Our laser setup consists of two 852-nm diode lasers, which are locked by saturated absorption spectroscopy (SAS). The first laser frequency is locked to the $6S_{1/2}$ $(F=4)\rightarrow 6P_{3/2}$ $(F'=4)$ transition by SAS, and the laser double passes through an acousto-optic modulator (AOM), which is placed at the focuses of one pair of lenses, acting as the trapping laser (in the MOT process) or the cooling laser (in the PGC process). This design makes sure that the beam does not move spatially when its frequency is changed by the voltage controlled oscillator. The second laser frequency is locked to the $6S_{1/2}$ $(F=3)\rightarrow 6P_{3/2}$ $(F'=3)$ transition by SAS, and the laser double passes through another AOM, acting as the repumping laser. In our standard Cs MOT, the trapping/cooling laser detuning D_c and the repumping laser detuning D_r are tuned to -15 MHz below the $F=4\rightarrow F'=5$ transition and the $F=3\rightarrow F'=4$ transition, respectively. The available maximum trapping/cooling beam intensity I_c is about 23 mW/cm^2, and the available maximum repumping beam intensity I_r is about 18 mW/cm^2. The trapping and the repumping beams are both expanded to about 15 mm in diameter. A charge-coupled device (CCD) is used to measure the cold atom dimension and the fluorescence intensity, which corresponds to the cold atom number. Usually, the cold Cs atom density and temperature in the MOT are measured to be about 5×10^{11} cm^{-3} and 70 μK, respectively.

After obtaining cold atoms in the MOT, we implement the PGC, release, and recapture processes to produce, release, and detect the sub-Doppler cooling cold atoms, respectively. The timing sequence runs as follows. The cold atoms are sub-Doppler cooled in the optical molasses by PGC after the precooling in the MOT, and then expand freely in the release process. In the following recapture process, the cold atoms are recaptured by the trapping and repumping beams. The PGC is a reliable and efficient method to achieve trapped cold atoms with a sub-Doppler temperature. As we can see from the introduction, the cooling laser frequency must be shifted away from the small red detuning to a larger red one and the cooling laser intensity must be turned down to a lower value. Usually, there are two frequently-used modes to change a physical value, which are step (short time, ∼ μs in our experiment) and ramp (long time, ∼ms in our experiment) modes. So there are four combination modes for changing the cooling laser frequency and intensity, i.e., frequency step + intensity ramp, frequency ramp + intensity step, frequency step + intensity step, and frequency ramp + intensity ramp, which are for simplicity marked as SR, RS, SS, and RR, respectively. We use the four different modes in the PGC process and compare the atom temperature in each mode. In the release process, the trapping and the repumping lasers are both turned off for the cold atoms to expand freely. In the recapture process, the trapping and the repumping lasers are suddenly turned on to recapture the cold atoms, and the CCD camera is triggered to record the fluorescence intensity and dimension, which correspond to the number and the volume of the cold atoms, respectively.

The process above is repeated at a period of 10 s. A program based on the Labwindows/CVI software is used to control the time sequence of the magnetic field, the trapping/cooling laser frequency and intensity, the repumping laser intensity, and the CCD acquisition. An AOM is used to change the laser frequency and intensity. An insulated gate bipolar transistor is used to switch the current on or off. The magnetic field can be completely turned on or off within 0.2 ms, according to our measurement.

3. Experimental results and discussion

3.1. Dependence of cold atom temperature on changing modes of the cooling laser

According to Section 2, there are SR, SS, RS, and RR modes to change the frequency and the intensity of the cooling laser. Figure 1 shows the expansion processes of the cold atoms in the optical molasses under the four different changing modes of the cooling laser. The start time in Fig. 1 is the finishing moment of the PGC. The solid dots, open triangles, open dots, and solid triangles represent the expansion processes of the SR, SS, RS, and RR modes, respectively. The interaction time for cooling, t_c, is 6 ms. The I_c and D_c of the cooling laser are 1 mW/cm^2 (for each beam) and $-10.5\Gamma_{Cs}$ red detuning below the $F=4\rightarrow F'=5$ transition, respectively, where $\Gamma_{Cs}=5.2$ MHz is the natural linewidth. The I_r is about 18 mW/cm^2. The error bars in the figure represent the standard deviations in mean value of four averaged, repeated experimental data (the error bars below have the same meaning).

We use the release and recapture method[23] to measure the temperature of the cold atoms, which has been described in Section 2. The temperature of the cold atoms can be obtained from the expansion process by using the equation

$$\sigma^2(t)=\sigma^2(0)+\frac{k_BT}{M}t^2, \tag{2}$$

where $\sigma(t)$ and $\sigma(0)$ are the Gaussian radii of the atom cloud at time t and the initial time, respectively, and T and M are the cold atom temperature and the atom mass, respectively. For simplicity, we list the temperatures for different cases in Fig. 2. We need to notice that the cold atom temperature in the PGC can also be influenced by many other factors, such as the balance of the cooling laser power, the elimination of the magnetic field, and even the property of the cold atoms in the MOT. However, the initial atom sample is the same for all the four cases and other parameters are the same except for the cooling laser changing mode. So we can focus on the influence of the cooling laser changing mode on the temperature. Comparing the cold atom temperatures under the SS and RS modes, which are 174 μK and 211 μK, respectively, we find that the step mode is better than the ramp mode for the cooling laser frequency. Comparing the cold atom temperatures under the RR and RS modes, which are 107 μK and 211 μK, respectively, we find that the ramp mode is better than the step mode for the cooling laser intensity. It then is predicted that the SR mode should be the best for the PGC. Our measurement shows that the expansion process of the cold atoms under the SR mode of PGC is really the slowest, corresponding to the lowest temperature of ∼18 μK under these experimental parameters.

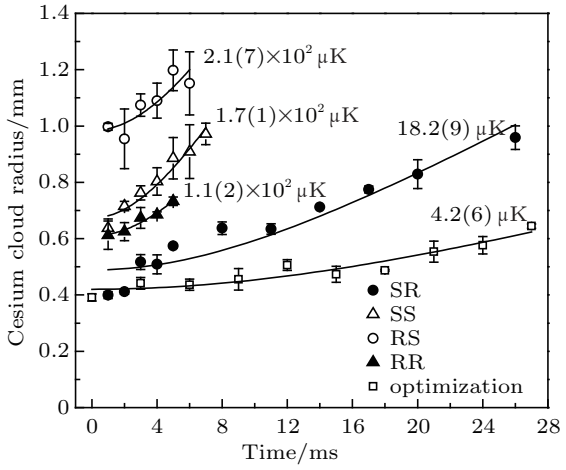


Fig. 1. Expansion processes of cold atoms under four different changing modes of the cooling laser and optimization. The solid lines are theoretical fitting curves with Eq. (2), from which the temperature can be obtained. The optimized parameters are as follows. The changing mode is SR, the PGC interaction time is 2 ms, the cooling laser detuning is $-6\Gamma_{Cs}$, the cooling and the repumping laser intensities are 1 mW/cm^2 and 18 mW/cm^2, respectively.

The explanation of our experimental results is given as follows. In our experiment, the trapping laser frequency is detuned to about $-3\Gamma_{Cs}$ below the atom transition in the MOT to cool the atoms. The scattering force on the atoms decreases as the cooling laser detuning decreases to be about $-10\Gamma_{Cs}$ below the atom transition in the PGC process. So the cold atom scattering due to the cooling laser in the PGC process also decreases. This means that we should change the cooling frequency as quickly as possible, which can be realized by the step mode. In the other side, when the cooling laser intensity is changed to a lower one by the ramp mode, the atoms will be cooled adiabatically[24] as the atom oscillation period in the optical molasses is small compared with the ramp time.[25] This means that the ramp mode for changing the cooling laser intensity is better than the step mode. From the above analysis, it is reasonable that the SR mode is the best for the PGC process, which has been verified in our experiments.

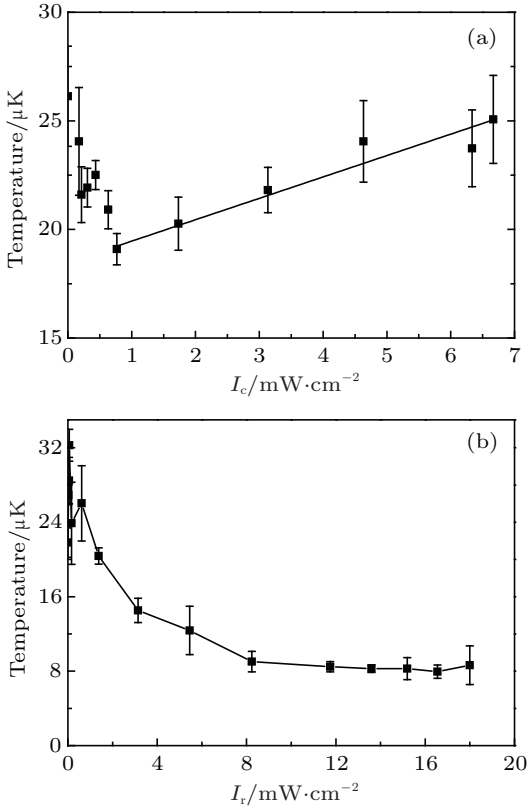


Fig. 2. Dependences of the cold atom temperature on (a) the cooling laser intensity and (b) the repumping laser intensity. The line in panel (a) is the linear fitting in the range from 0.8 mW/cm^2 to 6.7 mW/cm^2. The line in panel (b) is only used to guide the eyes. Both graphs show the heating effect, which arises from insufficient cooling when the laser power is low.

3.2. Dependence of cold atom temperature on cooling laser intensity and detuning

As equation (1) indicates that the temperature of the cold atoms in the PGC is influenced by the cooling laser detuning and intensity, we investigate the dependence of the sub-Doppler cooling cold atom temperature on the cooling laser detuning and intensity. We observe that the temperature decreases rapidly from about 150 μK to about 20 μK as the red detuning of the cooling beam changes from $-4\Gamma_{Cs}$ to $-6\Gamma_{Cs}$. Thus the temperature reaches a steady value when the cooling laser detuning is $-6\Gamma_{Cs}$.

Figure 2(a) shows the dependence of the cold atom temperature on the cooling laser intensity I_c. The cooling laser

changing mode is SR, and t_c is 1.5 ms. The I_r and D_c are 18 mW/cm^2 and $-8.6\Gamma_{Cs}$, respectively. It shows that the temperature increases linearly from about 19 μK to 24 μK as the cooling laser intensity of each beam increases from about 1 mW/cm^2 to 6.7 mW/cm^2. This is consistent with Eq. (1). However, the temperature becomes high when the cooling laser intensity is lower than 1.1 mW/cm^2, which is the saturation intensity for cesium.[26] This heating effect is also observed by other groups,[19] however, they did not give the reason.

We explain the heating effect as follows. As the cooling laser intensity decreases below the saturation intensity, the interaction between the atoms in the bright state ($F = 4$ state for the Cs atom) and the cooling laser is insufficient. This induces insufficient polarization gradient cooling. In order to verify our explanation, we change the repumping laser intensity in the PGC process in order to change the atoms in the bright state. The temperature of the cold atoms as a function of the repumping laser intensity in the PGC is shown in Fig. 2(b). The cooling laser changing mode is SR, and the interaction time is 1.5 ms. The D_c and I_c are $-10.5\Gamma_{Cs}$ and 1 mW/cm^2, respectively. It shows that the temperature does not change when the repumping laser intensity is larger than 8 mW/cm^2. However, the temperature increases as the repumping laser intensity decreases below 6 mW/cm^2. When the repumping laser power is high enough, it can make sure that nearly all the cold atoms lie in the bright state which can be cooled by the cooling laser. When the repumping laser is low, some cold atoms in the bright state are coupling to the dark state ($F = 3$ state for the Cs atoms), which have no contribution to the PGC. This makes the PGC cooling ineffective, which induces the heating effect.

3.3. Dependence of cold atom temperature on PGC interaction time

In the PGC process, the cold atom density decreases as the interaction time increases. However, too short time has little influence on the sub-Doppler cooling of the cold atoms. In order to find the appropriate interaction time, we investigate the dependence of the temperature of sub-Doppler cooling cold atoms on the PGC interaction time. The experimental result is shown in Fig. 3. The cooling laser changing mode is SR. The D_c, I_c, and I_r are $-10.5\Gamma_{Cs}$, 1 mW/cm^2, and 18 mW/cm^2, respectively. It shows that the temperature decreases rapidly from about 38 μK to 15 μK as the time increases from 0.2 ms to 3 ms and reaches a steady value after 3 ms.

We analyze the experimental result as follows. It is reasonable to suppose that the temperature variation rate $\Delta T/\Delta t$ is proportional to the force from the cooling laser, which is linearly dependent on the atom velocity V.[27] It needs to be declared that the velocity V only has a statistical significance. As V is proportional to temperature T, the temperature variation rate can be qualitatively described as

$$\frac{dT}{dt} = -\frac{1}{\tau}T. \tag{3}$$

Here τ is a characteristic time, the negative sign represents that the temperature decreases as the time increases. We use the solution of this equation, $T = T_0 \exp(-t/\tau)$, to fit the experimental data. The fitting result is shown with the solid line in Fig. 3. The characteristic time τ is 0.8 ms.

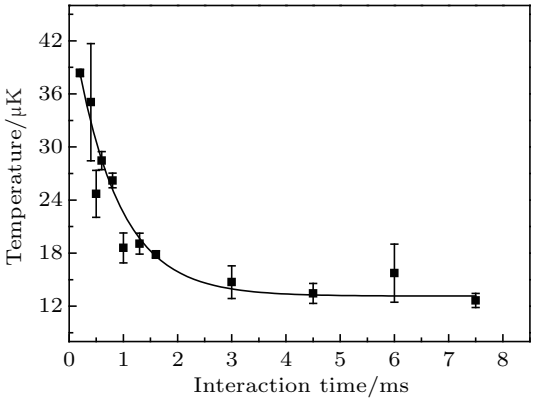


Fig. 3. Dependence of the cold atom temperature on the PGC interaction time. The fitting curve is based on the solution of Eq. (3). The characteristic time τ is fitted to be 0.8 ms.

Finally, the optimal parameters for the polarization gradient cooling in our ^{133}Cs experiment are listed below: the changing mode of the cooling laser is SR, the PGC interaction time is 2 ms, the cooling laser detuning and intensity in the PGC are $-6\Gamma_{Cs}$ and 1 mW/cm^2, respectively, and the repumping laser intensity is 18 mW/cm^2. Using these parameters, we capture a sample of cold atoms with the temperature of 4.2 ± 0.6 μK, compared to the temperature of 70 μK in the MOT, the number of atoms is 2×10^9. The TOF measurement is shown for the optimization case in Fig. 1. As the balance of the cooling laser power, the elimination of the magnetic field, and the property of the cold atoms in the MOT can affect the PGC temperature, it will help us to obtain a much lower temperature by optimizing these parameters. For example, we can adjust the powers of the six cooling lasers and stabilize their powers by a servo circuit. It is also useful to use some antimagnetic materials to reduce the magnetic influence from other equipments in the laboratory. These optimizations can only improve the cooling effect to ~ 1 μK. Usually, we can implement evaporation cooling on atoms in a magnetic trap or optical trap to obtain a much lower temperature.

4. Conclusion

We have systematically investigated the dependence of the cold cesium atom temperature in optical molasses on the controllable experimental parameters, which include the changing mode, the cooling laser frequency and intensity, and

the PGC interaction time. Our results show that the SR mode for changing the cooling laser, which means the cooling laser frequency is stepped to the setting value while its intensity is ramped to, is the best for the polarization gradient cooling of the cold atoms. It is predicted that the temperature decreases proportionally with decreasing trapping laser intensity in the range of 1–7 mW/cm^2. However, it is somewhat unusual that there is a heating effect when the cooling laser intensity is lower than 1 mW/cm^2, which is around the saturation intensity of the Cs atom. We believe that it arises from the insufficient interaction between the atoms in the bright state and the cooling laser. The explanation has been verified by the measurement of the relationship between the cold atom temperature and the repumping laser intensity. Finally, we introduce a statistical explanation and use an exponential decay formula to fit the cold atom temperature as a function of time. After the optimization, the lowest temperature of the cold cesium atoms achieved is about 4 μK with the number of atoms being 2×10^9. The optimization process can help us to understand how efficiently the atoms can be cooled to a sub-Doppler temperature by the PGC, and the experimental parameters are also meaningful for other cold atoms.

References

[1] Bize S, Laurent P, Abgrall M, Marion H, Maksimovic I, Cacciapuoti L, Grünert J, Vian C, Pereira dos Santos F, Rosenbusch P, Lemonde P, Santarelli G, Wolf P, Clairon A, Luiten, Tobar M and Salomon C 2005 *J. Phys. B* **38** S449

[2] Carnal O and Mlynek J 1991 *Phys. Rev. Lett.* **66** 2689

[3] Weber T, Herbig J, Mark M, Nägerl H C and Grimm R 2003 *Science* **299** 232

[4] Andrews M R, Townsend C G, Miesner H J, Durfee D S, Kurn D M and Ketterle W 1997 *Science* **275** 637

[5] Carr L D, DeMille D, Krems R V and Ye J 2009 *New J. Phys.* **11** 055049

[6] Garci-Ripoll J J, Zoller P and Cirac J I 2005 *J. Phys. B* **38** 567

[7] Chu S, Hollberg L, Bjorkholm J E, Cable A and Ashkin A 1985 *Phys. Rev. Lett.* **55** 48

[8] Kasevich M and Chu S 1992 *Phys. Rev. Lett.* **69** 1741

[9] Aspect A, Arimondo E, Kaiser R, Vansteenkiste N and Cohen Tannoudji C 1988 *Phys. Rev. Lett.* **61** 826

[10] Davis K B, Mewes M O, Joffe M A, Andrews M R and Ketterle W 1995 *Phys. Rev. Lett.* **74** 5202

[11] Dalibard J and Cohen-Tannoudji C 1989 *J. Opt. Soc. Am. B* **6** 2023

[12] Weiss D S, Riis E, Shevy Y, Ungar P J and Chu S 1989 *J. Opt. Soc. Am. B* **6** 2072

[13] Ungar P J, Weiss D S, Riis E and Chu S 1989 *J. Opt. Soc. Am. B* **6** 2058

[14] Fernandes D R, Sievers F, Kretzschmar N, Wu S, Salomon C and Chevy F 2012 *Europhys. Lett.* **100** 63001

[15] Kastberg A, Phillip W D, Rolston S L, Spreeuw R J C and Jessen P S 1995 *Phys. Rev. Lett.* **74** 1542

[16] Stecher H, Ritsch H, Zoller P, Sander F, Esslinger T and Hänsch T W 1997 *Phys. Rev. A* **55** 545

[17] Landini M, Roy S C, Trypogeorgos D, Fattori M, Inguscio M and Modugno G 2011 *Phys. Rev. A* **84** 043432

[18] Salomon C, Dalibard J, Phillips W D, Clairon A and Guellati S 1990 *Europhys. Lett.* **12** 683

[19] Wang B, Lü D S, Qu Q Z, Zhao J B, Li T, Liu L and Wang Y Z 2011 *Chin. Phys. Lett.* **28** 063701

[20] Hou J D, Li Y M, Yang D H and Wang Y Q 1998 *Acta Phys. Sin. (Oversea Edition)* **7** 881

[21] Han S L, Cheng B, Zhang J F, Xu Y F, Wang Z Y and Lin Q 2009 *Chin. Phys. Lett.* **26** 123702

[22] Ji Z H, Zhao Y T, Ma J, Xiao L T and Jia S T 2012 *J. Phy. Soc. Jpn.* **81** 104301

[23] Pradhan S and Jagatap B N 2008 *Rev. Sci. Instrum.* **79** 013101

[24] Shevy Y, Weiss D and Chu S 1989 *Spin Polarized Quantum Systems* (Singapore: World Scientific) pp. 287–294

[25] Castin Y and Dalibard J 1991 *Europhys. Lett.* **14** 761

[26] Steck D A http://steck.us/alkalidata

[27] Drewsen M, Laurent P, Nadir A, Santareli G, Clairon A, Castin Y, Grison D and Salomon C 1994 *Appl. Phys. B* **59** 283