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Enhanced optical molasses cooling for Cs atoms with largely detuned cooling lasers*

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We report a detailed study of the enhanced optical molasses cooling of Cs atoms, whose large hyperfine structure allows to use the largely red-detuned cooling lasers. We find that the combination of a large frequency detuning of about -110 MHz for the cooling laser and a suitable control for the powers of the cooling and repumping lasers allows to reach a cold temperature of ~ 5.5 μK. We obtain 5.1×10^7 atoms with the number density around 1×10^{12} cm^{-3}. Our result gains a lower temperature than that got in other experiments, in which the cold Cs atoms with the temperature of ~ 10 μK have been achieved by the optical molasses cooling.

Keywords: optical molasses, frequency detuning, magneto–optical trap, laser cooling

PACS: 32.10.Fn, 32.80.Qk, 37.10.–x, 37.10.De **DOI:** 10.1088/1674-1056/ab5fc6

1. Introduction

Bose–Einstein condensate (BEC) of atoms provides a good platform to explore exotic quantum phenomena, such as strongly interacting unitary gases,[1,2] artificial gauge potential,[3,4] phase transitions in optical lattice[5,6] and time-periodic driving of a quantum system.[7,8] The simple and most popular strategy to produce atomic BECs has been the initial loading of many atoms from laser cooling into a deep optical, magnetic or hybrid trap and the subsequent evaporation cooling of the atoms.[9–16] Laser cooling of atoms using magneto–optical traps (MOTs) and optical molasses is indispensable for the production of BEC for many different atomic species. The lower temperature and higher density for atomic sample after optical molasses or other laser cooling methods have advantages of achieving larger BECs within shorter evaporation time, which has helped to promote further significant applications of BECs.

Optical molasses known as a kind of sub-Doppler cooling with the red-detuned cooling laser driving the cycling transition of D_2 line enables the temperature of atoms cooled below the Doppler limit [17–19]. More careful studies have shown that an optimized-optical molasses cooling for the K atoms with the temperature of $T \approx 25$ μK can be achieved by adiabatically sweeping the frequency detunings and powers of cooling and repumping lasers.[20,21] For the bosonic isotopes of Li and Na atoms, the excited hyperfine levels on the D_2 line have narrow energy split, which weakens the efficiency of optical molasses cooling. In a different approach, gray-molasses (GM) with a blue-detuned cooling laser driving the transitions of D lines was proposed and used to obtain an efficient cooling before the evaporation of atoms.[22–24] An enhanced Λ-gray molasses (ΛGM) has been developed to achieve the lower temperature for ^{6}Li,[25,26] ^{23}Na,[27,28] ^{39}K,[29] ^{40}K,[26,30] and ^{41}K[31] atoms, and then allows to achieve the rapid production of large BECs. An efficient ΛGM has also been demonstrated in the ^{87}Rb[32] and ^{133}Cs[33] atoms.

Considering the particular collision characteristics of Cs atoms, which require a lower temperature against the inelastic endothermic collisions in the subsequent evaporation cooling, a three-dimensional (3D) degenerated Raman sideband cooling (dRSC) is used to reach a cold temperature of $T \approx 1$ μK[34,35] and facilitates the formation of Cs BECs.[12,13] Recently, 3D dRSC is implemented on ^{39}K atoms to achieve a cold temperature as low as 1.3 μK, which is the so far coldest temperature for ^{39}K atoms before evaporation.[36] The dRSC also polarizes the atomic sample in a desired Zeeman state. For the ^{87}Rb[37] and ^{133}Cs[38] atoms trapped in a 2D optical lattice operating at the wavelength $\lambda = 1064$ nm, the dRCS has been demonstrated to enable the production of quantum gases by the direct laser cooling.

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Compared to the complicated dRSC, although ΛGM has been used for the D_2 transitions of Cs atoms to achieve a low temperature of $T = 1.7$ μK as similar to the one reached by the dRSC, but the atoms are populated in the hyperfine $F = 3$ state. An indispensable optical pumping is used to polarize the Cs atoms in the $F = 3$, $mF = 3$ Zeeman state, in which the inelastic endothermic collisions of Cs atoms are suppressed in the subsequent evaporation cooling. In this paper, the enhanced optical molasses cooling has been demonstrated for Cs atoms to produce a lower temperature of ~ 5.5 μK than other experiments of optical molasses cooling. For the lower temperature obtained by ΛGM the scattering photons in the optical pumping could heat the atomic cloud.[39–41] However, this heating can be ignored for the atoms after optical molasses due to the relative high temperature.[42] Our result might have a similar effect with the ΛGM after the optical pumping. The dependence of the optical molasses cooling of Cs atoms on the frequency detuning and power of the cooling laser and the power of repumping laser is measured, a large frequency detuning for the cooling laser and the suitable control for the powers of the cooling and repumping lasers lead to the enhanced optical molasses cooling.

2. Experimental setup and process

The relevant energy levels of Cs atoms and the frequencies of lasers are shown in Fig. 1. The frequency of a reference laser is downward shifted through the double-pass modulations of acoustic–optical modulator (AOM) and then locked to the $F = 4 \rightarrow F' = 5$ cycling transition of the D_2 line by the polarization spectroscopy of Cs atoms. The actual frequency of reference laser is detuned by $\Delta_{rf} = +220$ MHz referring to the transition line. The cooling laser is mixed with the frequency-locked reference laser through a glass and the beat note is produced by interfering these two lasers on a fast photodetector. The beat frequency is compared to the output frequency of a voltage-controlled oscillator (VCO) contained in the phase detector, which produces a certain voltage signal corresponding to the obtained beat frequency. The error signal is created by subtracting the voltage signal of phase detector from the control signal, and then is fast fed to the current and PZT ports of cooling laser by a home-built circuit. The frequency of the stabilized cooling laser can be fast changed by adjusting the control signal. The frequency of cooling laser after a power amplifier is shifted by +210 MHz using the double pass modulations of AOM. During MOT, the beat frequency is controlled with $f = -455$ MHz.

Cs atoms are heated to a temperature of 56 °C in an atomic oven, and then are collimated and cooled in a cold nipple tube with the temperature-controlled thermoelectric coolers. The ejected high-flux beam of Cs atoms is slowed down by a Zeeman slower and collected in a high-vacuum main chamber by using MOT. MOT is constructed with six cooling lasers, one repumping laser and a pair of anti-Helmholtz coils. Each cooling laser is detuned by $\Delta_{cool} = -15$ MHz from the resonant cycling transition and has a power of $P_{cool} = 6$ mW. A 3.5 mW repumping laser is detuned by $\Delta_{rep} = -10$ MHz from the $F = 3 \rightarrow F' = 4$ transition. A pair of anti-Helmholtz coils with 20 turns in each are operated at the current of $I = 8$ A, the magnetic field gradient is $\partial B/\partial z = 13$ Gs/cm (1 Gs $= 10^{-4}$ T). After 6 s of MOT loading, we can trap $\sim 4.5 \times 10^8$ cold atoms.

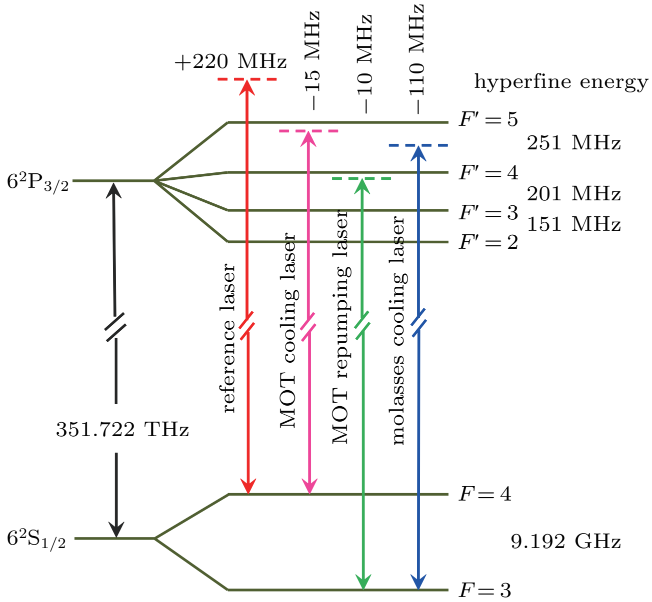

Fig. 1. Energy levels of ^{133}Cs atoms and frequency detunings of relevant lasers to the resonant transition lines. The frequency-locked reference laser based on the polarization spectroscopy of Cs atoms is detuned to the $F = 4 \rightarrow F' = 5$ cycling transition by $\Delta_{rf} = +220$ MHz. The cooling laser is stabilized by locking the beat frequency with the reference laser. The frequency detuning Δ_{cool} of cooling laser relative to the resonant cycling transition is quickly tuned by the controlled beat frequency. The cooling laser with a larger Δ_{cool} is essential in the optical molasses cooling.

The compressed magneto–optical trap (CMOT) is implemented by increasing the magnetic field gradient to $\partial B/\partial z = 27$ Gs/cm, increasing the frequency detuning of cooling laser to $\Delta_{cool} = -40$ MHz, reducing the power of repumping laser to $P_{rep} = 1.5$ mW. The Δ_{cool} is fast tuned by changing the control signal to tune the beat frequency between the frequency-lock reference laser and the cooling laser. The cooling laser can be quickly relocked from unlocking and the error signal recoveries to zero. In the process of changing Δ_{cool}, we do not find that the atomic sample is heated and the laser power has not any loss compared to the method of shifting the laser frequency using the double pass modulations of AOM. After 35-ms CMOT, the atomic density is greatly increased to 10^{12} cm^{-3}.

At the end of CMOT, $\partial B/\partial z$ is quickly turned off. At the beginning of the optical molasses cooling, the frequency of cooling laser is jumped to another value with an optimized detuning to the resonant cycling transition, and this detuning is typically larger than the detuning used in CMOT. P_{cool} is also tuned to a suitable value by the AOM for a good cooling efficiency. We find that $P_{\rm rep}$ has an effect on the number of cooled atoms and has to be optimized. In the sequence, the repumping laser is turned off for 1 ms before the end of optical molasses. After the optical molasses cooling, the atoms are populated in the $F=3$ hyperfine state, which is the desired state for the future experiments. During the optical molasses, the three pairs of coils used to compensate the stray magnetic fields are also crucial to achieve a low atomic temperature.

3. Results and analysis

In the experiment, the absorption imaging is used to diagnose the distribution of atomic column density, where the probe laser propagates along the z axis. The atomic profile is given by fitting the Gaussian function to the summed optical density along the x and y axes. Based on the $1/e$ width in each axis and the peak density obtained by the Gaussian fitting, we can calculate the number of atoms. The atomic temperature is determined by fitting the variation of atomic width with the flight time to the formula,

$$\sigma_{i,t}=\sqrt{\sigma_{i,0}^2+\frac{2k_{\rm B}T_i}{m}t^2}, \tag{1}$$

where the subscript i represents the x or y axis, $\sigma_{i,t}$ is the $1/e$ width of atom cloud at the flight time t, and $k_{\rm B}$ is the Boltzmann constant.

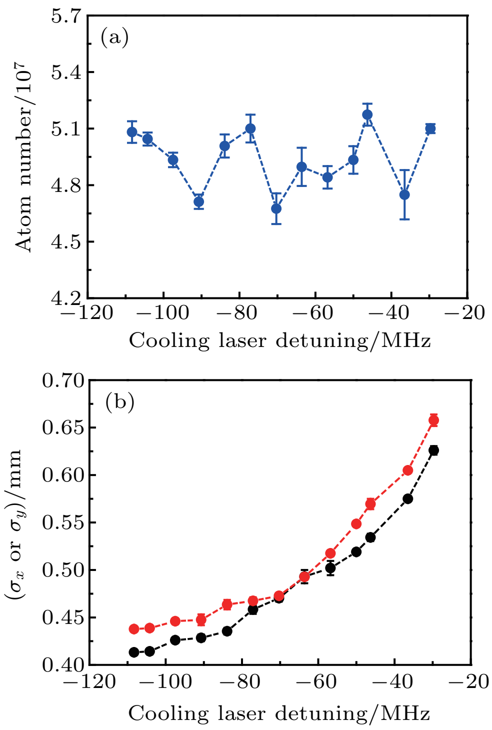

Fig. 2. The number and $1/e$ width of cooled Cs atoms at the flight time of $t=10$ ms after optical molasses as the functions of the frequency detuning $\Delta_{\rm cool}$ of the cooling laser relative to the $F=4\rightarrow F'=5$ cycling transition. The blue dots represent the atom number N, the red and black dots are the $1/e$ widthes (σ_x and σ_y) of atomic column density along x and y axes, respectively. Each datum point is the average result of five measurements. The dashed lines are plotted for guiding the eye.

We first study the effect of $\Delta_{\rm cool}$ on the number N and temperature T of atoms. The number of atoms does not show a strong dependence on $\Delta_{\rm cool}$ in Fig. 2(a). This illustrates that there are enough photons from cooling lasers to be scattered by atoms, although the increasing $\Delta_{\rm cool}$ leads to the reducation of the scattering rate for individual atom. In the measurement of T, a lower T exhibits the smaller σ_x and σ_y at the same flight time t, which can be explained by Eq. (1). Figure 2(b) shows the variations of σ_x and σ_y at $t=10$ ms with $\Delta_{\rm cool}$. The result illustrates that the T decreases with the increasing $\Delta_{\rm cool}$. When $\Delta_{\rm cool}$ reaches to -90 MHz, the σ_x or σ_y shows a small variation with the continuously increasing $\Delta_{\rm cool}$. In principle, the lowest temperature obtained by sub-Doppler cooling is independent on $\Delta_{\rm cool}$,[20] but a large $\Delta_{\rm cool}$ enables the low scattering rate of photons by the atoms and reduces the heating in the effective cooling process. So the relative large $\Delta_{\rm cool}$ has a good cooling result, due to a broad hyperfine structure of Cs excited state. The σ_x or σ_y reaches minimum at the frequency detuning of $\Delta_{\rm cool}=-105$ MHz. Here $\Delta_{\rm cool}$ is set on -110 MHz for a cold T with a relatively large N.

At the optimized frequency detuning of $\Delta_{\rm cool}=-110$ MHz, the variations of N and T with $P_{\rm cool}$ are shown in Fig. 3. The measurement is performed at $t=10$ ms after optical molasses cooling. Compared to the dependence of N on $\Delta_{\rm cool}$, $P_{\rm cool}$ has a large effect on the number of atoms, and the number of atoms decreases with the increasing $P_{\rm cool}$. This is mainly attributed to that the decreased $P_{\rm cool}$ lowers the total scattering rates of photons by the atoms, and so many atoms escape from the capture range. The $P_{\rm cool}$ has the similar effect on the σ_x and σ_y. The variation of σ_x or σ_y with $P_{\rm cool}$ shows that a low $P_{\rm cool}$ (<2 mW) reduces the efficiency of optical molasses cooling. Similar to the explanation for the effect of $P_{\rm cool}$ on the atom number, the heating of atoms at the low $P_{\rm cool}$ can be understood by the decreased scattering rates of photons. At the low scattering rates, the atoms can not be efficiently cooled. Although the σ_x and σ_y reach the minimum values at the power of 2.8 mW, N has a decrease by a factor of $>10\%$. In comparison, the power of $P_{\rm cool}=6$ mW for each cooling laser beam is chosen as an optimized parameter.

In order to polarize the cooled atoms in the $F=3$ hyperfine ground state, the repumping laser needs to be turned off previous to the end of optical molasses, where an optimized time given as 1 ms in the experiment. The effect of the repumping laser on the efficiency of optical molasses cooling is studied by measuring the variations of N with the frequency detuning $\Delta_{\rm rep}$ to the $F=3\rightarrow F'=4$ transition and the power $P_{\rm rep}$ of repumping laser. As shown in Fig. 4, N is strongly dependent on $P_{\rm rep}$. The measurement shows that the repumping laser with enough power is necessary to prevent the atoms from populating in the dart state $F=3$, in which the atoms cannot scatter the photons from the cooling laser. To achieve the maximum N, P_{rep} is fixed at 4.9 W. On the contrary, Δ_{rep} has little influence on N. Besides, we find that P_{rep} and Δ_{rep} have little influence on T. The Δ_{rep} remains the same value with the one used in the MOT and CMOT processes.

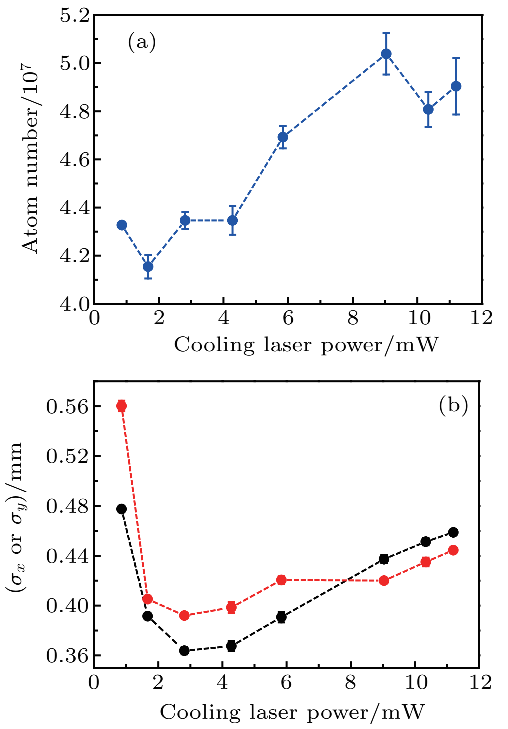

Fig. 3. The number and 1/e width of the cooled Cs atoms at the flight time of $t = 10$ ms after optical molasses as the functions of the power P_{cool} of each cooling laser beam. The blue dots represent the atom number N, the red and black dots are the 1/e widths (σ_x and σ_y) of atomic column density along x and y axes, respectively. Each datum point is the average result of five measurements. The dashed lines are plotted for guiding the eye.

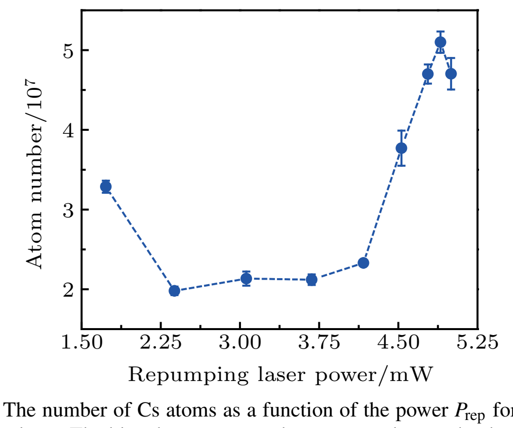

Fig. 4. The number of Cs atoms as a function of the power P_{rep} for the repumping laser. The blue dots represent the atom number N, the dashed line is plotted to guide to the eye. Each datum point is the average result of five measurements.

The T obtained by optical molasses with the optimized parameters is measured by the time of flight. Figure 5 shows the variations of σ_x and σ_y with t and T given by fitting the data to Eq. (1). The cooled atoms have the temperature of $T_x = 5.5 \pm 0.47$ μK and $T_y = 6 \pm 0.29$ μK with $N = 5.1 \times 10^7$, the atomic density is around 1×10^{12} cm^{-3}. Compared to the result of the previous optical molasses for the Cs BEC experiment, the atom temperature is lower by a factor of ~ 2. Although all parameters have been optimized very carefully in the optical molasses cooling of Cs atoms, the obtained cold temperature is mainly attributed to the large frequency detuning of cooling laser.

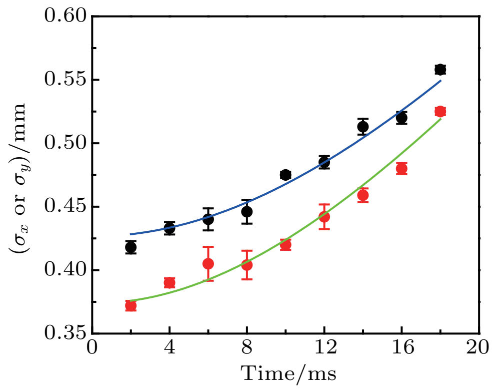

Fig. 5. The 1/e width of atomic cloud as a function of the flight time t. The black and red dots represent the 1/e widthes (σ_x and σ_y) of atomic column density along x and y axes, respectively. Each datum point is the average result of five measurements. The solid lines are obtained by fitting the data to Eq. (1). The fitting gives the atomic temperature of $T_x = 5.5 \pm 0.47$ μK and $T_y = 6 \pm 0.29$ μK.

4. Conclusion

We have demonstrated an enhanced optical molasses cooling of Cs atoms with a large frequency detuning for the cooling laser and the optimized powers for the cooling and repumping lasers. Compared to the cooling results of the previous optical molasses, a lower temperature has been achieved by using a larger frequency detuning for the cooling laser. We find that the fast jump of the cooling laser frequency to another value with a large detuning relative to the resonant cycling transition dose not induce the heating and loss of the atomic sample. Besides, our measurement shows that the powers of the cooling and repumping lasers have a great influence on the atom number compared to the atomic temperature. Since the enhanced optical molasses has a similar effect with the ΛGM after the optical pumping for the further evaporation cooling, it is valuable to implement a relatively simple but effective optical molasses cooling with a suitable control on the frequency of cooling laser and powers of the cooling and repumping lasers.

References

[1] Makotyn P, Klauss C E, Goldberger D L, Cornell E A and Jin D S 2014 *Nat. Phys.* **10** 116
[2] Eigen C, Glidden J A P, Lopes R, Cornell E A, Smith R P and Hadzibabic Z 2018 *Nature* **563** 221
[3] Lin Y J, Jiménez-García K and Spielman I B 2014 *Nature* **471** 83
[4] Dalibard J, Gerbier F, Juzeliūnas G and Öhberg P 2011 *Rev. Mod. Phys.* **83** 1523
[5] Greiner M, Mandel O, Esslinger T, Hänsch T W and Bloch I 2002 *Nature* **415** 39
[6] Bloch I, Dalibard J and Zwerger W 2008 *Rev. Mod. Phys.* **80** 885
[7] Parker C V, Ha L C and Chin C 2013 *Nat. Phys.* **9** 769
[8] Eckardt A 2017 *Rev. Mod. Phys.* **89** 011004
[9] Barrett M D, Sauer J A and Chapman M S 2001 *Phys. Rev. Lett.* **87** 010404

[10] Jiang J, Zhao L, Webb M, Jiang N, Yang H and Liu Y 2013 *Phys. Rev. A* **88** 033620
[11] Davis K B, Mewes M O, Andrews M R, van Druten N J, Durfee D S, Kurn D M and Ketterle W 1995 *Phys. Rev. Lett.* **75** 3969
[12] Kraemer T, Herbig J, Mark M, Weber T, Chin C, Nägerl H C and Grimm R 2004 *Appl. Phys. B* **79** 1013
[13] Hung C L, Zhang X B , Gemelke N and Chin C 2008 *Phys. Rev. A* **78** 011604
[14] Lin Y J, Perry A R, Compton R L, Spielman I B and Porto J V 2009 *Phys. Rev. A* **79** 063631
[15] Jenkina D L, McCarron D J, Koppinger M P, Cho H W, Höpkins S A and Cornish S L 2011 *Eur. Phys. J. D* **65** 11
[16] Wang P J, Xiong D Z, Fu Z K and Zhang J 2011 *Chin. Phys. B* **20** 016701
[17] Raab E L, Prentiss M, Cable A, Chu S and Pritchard D E 1987 *Phys. Rev. Lett.* **59** 2631
[18] Dalibard J and Cohen-Tannoudj C 1989 *J. Opt. Soc. Am. B* **11** 2023
[19] Weiss D S, Riis E, Shevy Y, Ungar P J and Chu S 1989 *J. Opt. Soc. Am. B* **11** 2072
[20] Landini M, Roy S, Carcagní L, Trypogeorgos D, Fattori M, Inguscio M and Modugno G 2011 *Phys. Rev. A* **84** 043432
[21] Gokhroo V, Rajalakshmi G, Easwaran R K and Unnikrishnan C S 2011 *J. Phys. B* **44** 115307
[22] Satter C L, Tan S and Dieckmann K 2018 *Phys. Rev. A* **98** 023422
[23] Kim K, Huh S J, Kwon K and Choi J Y 2019 *Phys. Rev. A* **99** 053604
[24] Salomon G, Fouché L, Lepoutre S, Aspect A and Bourdel T 2014 *Phys. Rev. A* **90** 033405
[25] Burchianti A, Valtolina G, Seman J A, Pace E, De Pas M, Inguscio M, Zaccanti M and Roati G 2014 *Phys. Rev. A* **90** 043408
[26] Sievers F, Kretzschmar N, Fernandes D R, Suchet D, Rabinovic M, Wu S, Parker C V, Khaykovich L, Salomon C and Chevy F 2015 *Phys. Rev. A* **91** 023426
[27] Shi Z L, Li Z L, Wang P J, Meng Z M, Huang L H and Zhang J 2018 *Chin. Phys. Lett.* **35** 123701
[28] Colzi G, Durastante G, Fava E, Serafini S, Lamporesi G and Ferrari G 2016 *Phys. Rev. A* **93** 023421
[29] Nath D, Easwaran R K, Rajalakshmi G and Unnikrishnan C S 2013 *Phys. Rev. A* **88** 053407
[30] Bruce G D, Haller E, Peaudecerf B, Cotta D A, Andia M, Wu S, Johnson M Y H, Lovett B W and Kuhr S 2017 *J. Phys. B* **50** 095002
[31] Chen H Z, Yao X C, Wu Y P, Liu X P, Wang X Q, Wang Y X, Chen Y A and Pan J W 2016 *Phys. Rev. A* **94** 033408
[32] Rosi S, Burchianti A, Conclave S, Naik D S, Roati G, Fort C and Minardi F 2018 *Sci. Rep.* **8** 1301
[33] Hsiao Y F, Lin Y J and Chen Y C 2018 *Phys. Rev. A* **98** 033419
[34] Kerman A J, Vuletić V, Chin C and Chu S 2000 *Phys. Rev. Lett.* **84** 439
[35] Treutlein P, Chung K Y and Chu S 2001 *Phys. Rev. A* **63** 051401
[36] Gröbner M, Weinmann P, Kirilov E and Nägerl H C 2017 *Phys. Rev. A* **95** 033412
[37] Hu J Z, Urvoy A, Vendeiro Z, Crépel V, Chen W L and Vuletić V 2017 *Science* **358** 1078
[38] Solano P, Duan Y H, Chen Y T, Rudelis A, Chin C and Vuletić V 2019 *Phys. Rev. Lett.* **123** 173401
[39] Tierney P 2009 "Magnetic trapping of an ultracold (87)Rb–(133)Cs atomic mixture", Ph. D. dissertation (Durham: Durham University)
[40] Landini M, Roy S, Roati G, Simoni A, Inguscio M, Modugno G and Fattori M 2012 *Phys. Rev. A* **86** 033421
[41] Han D J, Wolf S, Oliver S, McCormick C, DePue M T and Weiss D S 2000 *Phys. Rev. Lett.* **85** 724
[42] Smirne G 2005 "Experiments with Bose-Einstein Condensates in Optical Traps" Ph. D. dissertation (Oxford: University of Oxford)