Laser & Optoelectronics Progress

Effective Slowing and Trapping of Cs Atoms in an Ultrahigh-Vacuum Apparatus

Li Yuqing[1,2], Du Huiying[1], Wang Yunfei[1], Wu Jizhou[1,2], Liu Wenliang[1,2], Li Peng[3], Fu Yongming[3], Ma Jie[1,2*], Xiao Liantuan[1,2], Jia Suotang[1,2]

[1]*State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Laser Spectroscopy, College of Physics and Electronics Engineering, Shanxi University, Taiyuan* 030006, *Shanxi, China*;

[2]*Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan* 030006, *Shanxi, China*;

[3]*College of Physics and Electronic Engineering, Shanxi University, Taiyuan* 030006, *Shanxi, China*

Abstract We report the effective slowing and trapping of Cs atoms in an ultrahigh-vacuum apparatus. The heated Cs atoms in an oven are slowed using a Zeeman slower after the oven chamber and then trapped using a magneto-optical trap in a science chamber. Compared to the traditional vacuum pressure of ~10^{-7} Pa determined by the vapor pressure of Cs atoms in the oven chamber, the designed cold nipple and differential pumping tube are used between the oven and the oven chamber to achieve a lower vacuum pressure of ~3.6×10^{-9} Pa. This is beneficial for achieving and maintaining an ultrahigh vacuum in the science chamber. We demonstrate the performance of our apparatus through the effective slowing of Cs atoms and an optimal magneto-optical trap.

Key words ultrahigh-vacuum apparatus; Cs atom; Zeeman slower; magneto-optical trap

中图分类号 O46 **文献标志码** A **DOI**: 10.3788/LOP231417

1 Introduction

Experiments on laser cooling and manipulation of neutral atoms have been shown to have several important applications in the fundamental and applied sciences, including quantum entanglement[1-3], quantum simulation[4-6], and precision measurement[7-11]. Applications typically require a large number of cold atoms to be microscopically trapped in a high-vacuum chamber to compensate for large losses in subsequent experimental processes. Hence, the design of the vacuum apparatus has become crucial. A high-flux beam of atoms ejected from an atomic source into the magneto-optical trap (MOT) chamber is ideal for trapping more atoms. Most vacuum systems contain differential pumping sections and tubes for an ultrahigh vacuum of ~10^{-9} Pa in the science chamber, where a better vacuum allows a longer lifetime for an ultracold atomic cloud.

The conditions for both a large atomic number and high vacuum are commonly met using a vacuum system with a Zeeman slower[12-14] or a two-dimensional MOT[15-17]. In comparison, the Zeeman slower method requires fewer optical components, less alignment, and a lower laser power. The vacuum apparatus, composed of an atomic oven and a Zeeman slower, can provide more atomic samples and has a high vacuum. The atoms are heated in the oven to produce high-flux atomic beams. The Zeeman slower is used to lower the atomic velocity, and the long tube of the Zeeman slower also creates a pressure difference of approximately 10 Pa between the science and oven chambers. Therefore, the use of a Zeeman slower is highly attractive for many atomic species. To date, all alkali metal atoms and some alkaline earth metal atoms have been cooled to quantum degeneration in a vacuum apparatus using a Zeeman slower[18-21].

To obtain an ultrahigh vacuum in the science chamber, it is preferable for the oven chamber to have a high vacuum of ~10^{-8} Pa. However, particularly for Cs atoms, the high saturated vapor pressure results in a

收稿日期：2023-05-31；**修回日期**：2023-06-30；**录用日期**：2023-07-12；**网络首发日期**：2023-07-22

基金项目：国家自然科学基金(62020106014,92165106,62175140,12074234)、长江学者与创新团队发展计划(IRT17R70)、高等学校学科创新引智计划项目(D18001)、山西省应用基础研究项目(202203021224001)

通信作者：*mj@sxu.edu.cn

vacuum pressure of $\sim 10^{-7}$ Pa in the oven chamber. A long copper nozzle with a small diameter (1.5 mm) is used to prevent Cs atoms from accumulating in the oven chamber[20], thus avoiding the limit of the saturated vapor pressure on the vacuum. A potential question is whether thin and long nozzles are easily blocked by the ejected Cs atoms. In this study, we use a cold nipple and differential pumping copper tube between the oven and oven chamber to obtain a lower vacuum pressure in the oven chamber. A good vacuum in the oven chamber makes it easier to obtain an ultrahigh vacuum in the science chamber for the cold-atom experiments. The dependence of vacuum pressure in the oven chamber on the temperature of the designed nipple is measured experimentally and theoretically. The details of the analysis and measurement of the Zeeman slower are presented. The designed ultrahigh-vacuum apparatus is also used to slow down the Cs atoms and obtain an optimized MOT in the science chamber.

2 Design and calculation

Our vacuum apparatus is divided into three main parts by differential pumping tubes: an atomic oven, oven chamber, and main science chamber, as shown in Fig. 1. The Cs oven consists of a copper tube and an all-metal angle valve. A large number of Cs atoms heated in the oven are first cooled and then accumulated in a cold nipple tube. The ejected atomic beam is slowed by a Zeeman slower and captured using an MOT in a science chamber. A 50 L ion pump and a Ti sublimation pump are used to maintain the vacuum in the oven chamber. The science chamber is connected to a 150 L ion pump and a Ti sublimation pump. The Zeeman slower tube maintains a vacuum pressure difference of approximately 10 Pa between the science and oven chambers. The main vacuum components constituting the vacuum apparatus are connected and assembled along a collimated atomic beam with a total length of 1.77 m.

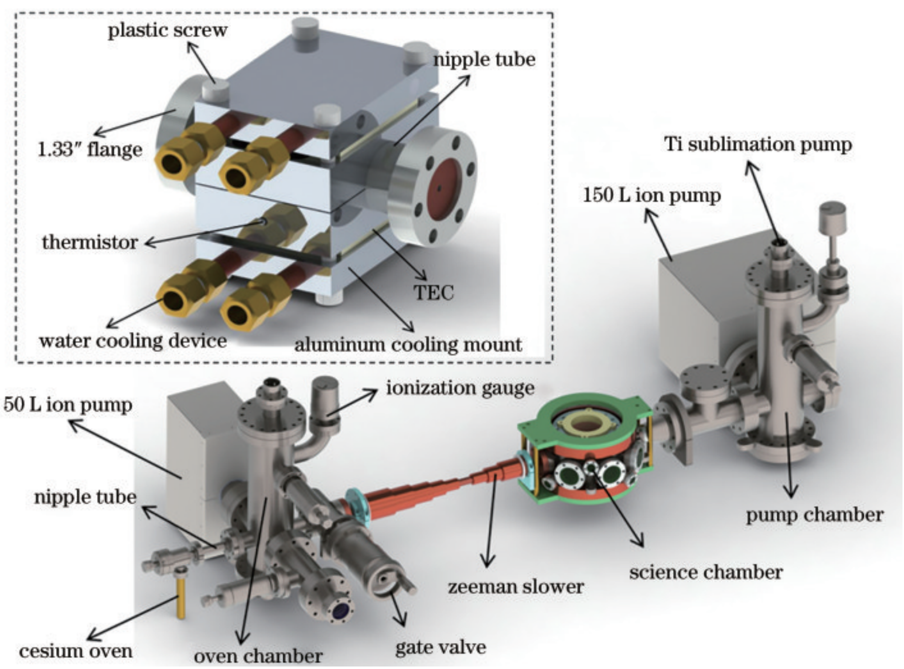

Fig. 1　Schematic of the vacuum apparatus (the Cs atomic oven is heated up to 60 ℃ to provide a high flux of atoms. A Zeeman slower is installed between the gate valve connected the oven chamber and the science chamber. Two ion pumps with the speeds of 50 L/s and 150 L/s are connected with the oven chamber and the science chamber, respectively. In addition, each of the oven chamber and the science chamber has a Ti sublimation pump. The designed cold nipple is enlarged in the dashed box. The cold nipple consists of a 60 mm long tube connected with two 1.33″ flanges, the temperature control unit, and the water cooling device. The temperature control unit includes two TECs, a thermistor, the temperature controller and the aluminum mount. The plastic screws are used to prevent the heat conduction)

The designed nipple consists of a 60 mm long tube and two 1.33″ flanges, as shown in the dashed box in Fig. 1. On each side of the nipple tube, the flange has a hole with a diameter of 2 mm in its center. The atomic beam is collimated using two holes in the nipple and enters the science chamber through a Zeeman slower tube. The use of a nipple does not reduce the number of Cs atoms in the MOT because the divergence angle determined by the atomic source and the hole on the right side of the cold nipple is larger than the divergence angle determined by the atomic source and inner diameter of the slower tube at its end. To prevent the large number of Cs atoms that have accumulated in the nipple from entering the oven chamber, the nipple is effectively cooled using two thermoelectric coolers (TECs) to ≤10 ℃. The heat from the back of the TECs is quickly removed via water cooling. A low nipple temperature is beneficial for obtaining a high vacuum in the oven chamber. To slow down the ejected high-flux atomic beams collimated by the nipple, a Zeeman slower is installed between the all-metal gate valve and the science chamber. The gate valve is connected to the oven chamber to facilitate replacement of the Cs source in the future. The length and inner diameter of the slower tube are 42 cm and 8 mm, respectively. The slightly focused, slowing laser is sufficiently detuned to have a negligible influence on the trapped cold atoms when passing through the MOT. A weak repumping laser with large detuning is used to maintain efficient transitions during the deceleration process.

As the key components of a Zeeman slower, the pairs of coils wound on the slower tube are properly designed to guarantee maximum deceleration for the atoms along the slower tube, as shown in Fig. 2. The maximum deceleration[22] is obtained when the atom is in resonance with the sufficiently saturated laser beam and is given as

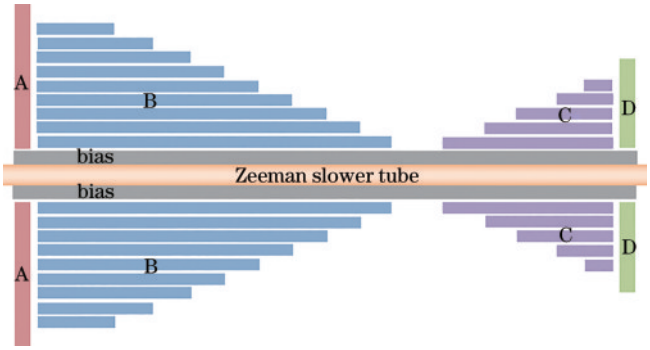

Fig. 2 Construction of a Zeeman slower for Cs atoms (the Zeeman slower consists of a slower tube with 8 mm inner diameter and five segments of magnetic field coils, which are manufactured by using 2 mm square copper wires. The two layers of bias coils at the bottom create an uniform magnetic field of 45 G at a current of 3.4 A and each layer has 180 turns. The structurally tapered coils are wrapped on the surface of the bias coils and have the optimized currents of 1.0, 1.2, −1.2, and −3 A for the A, B, C, and D

$$a_{\max}=\frac{\Gamma}{2}\frac{\hbar\kappa}{m}, \tag{1}$$

where $\Gamma=2\pi\times5.2$ MHz is the linewidth of Cs atoms, $\hbar$is the Planck's constant, k is the wave vector, and m is the atomic mass. Due to the imperfect field profile of the Zeeman slower, the limited intensity of the laser beam, and the distribution of atomic velocity, the actual deceleration in the slower is

$$a=\eta a_{\max}, \tag{2}$$

where η is a fraction representing the efficiency of the Zeeman slower[23-24].

To compensate for the Doppler shift observed by the atoms moving with constant deceleration, the B-field profile is be given by [22]

$$B(z)=\frac{\hbar}{\mu}\left(\delta+k\sqrt{v_i^2-2az}\right), \tag{3}$$

where μ is the magnetic moment of the $6S_{1/2}, F=4\rightarrow 6P_{2/3}, F=5$ transition of Cs atoms, δ is the detuning from the atomic transition at zero-field, and v_i is the atomic velocity before the Zeeman slower. We assume that after leaving the cold nipple, the atoms have the same velocity v_i until they enter the Zeeman slower, where the temperature of the cold nipple is determined by $v_i=\sqrt{8k_BT/(\pi m)}=211.7$ m/s. The final velocity at the end of the slower is expressed as

$$v_f=\sqrt{v_i^2-2aL}, \tag{4}$$

where L=42 cm is the length of the slower. If we have a high fraction of $\eta\geqslant0.85$, the atoms are slowed down to at least $v_f=74.6$ m/s.

As shown in Fig. 2, the coils wound on the slower tube are divided into five parts, which includes the bias coils and tapered A, B, C, and D segments. The bias coils consist of two layers, and each layer has 180 turns of 2 mm square copper wire. The bias coils operate at a current of 3.4 A and create a uniform bias field of $B=45$ G along the direction of the slower. Segments A, B, C, and D are four different sets of tapered coils wound on the bias coils. Coils A, B, C, and D contain 33, 626, 94, and 18 turns, respectively. The tapered slower coils work at currents of 1.0 A (A segment), 1.2 A (B segment), 1.2 A (C segment), and −3.0 A (D segment). The current in each set of coils is individually controlled using an electronic circuit in which field-effect transistors are used to stabilize the current. The atoms are slowed by a Zeeman slower and captured in the center of the science chamber using the MOT. A good vacuum environment is crucial for cold atom experiments, particularly for creating atomic

BEC. We estimate the vacuum pressure after each differential pumping section to ensure a high vacuum in the science chamber. The vacuum pressure in the cold nipple tube is estimated using the vapor pressure of the Cs atoms. The controlled temperature of 10 ℃. indicates a vacuum pressure of $P_0=4.4\times10^{-5}$ Pa, which is regarded as the starting point for calculating the vacuum pressure in the vacuum devices after the nipple. The vacuum conductance C of a long round tube with diameter d and length l is given by

$$C=\frac{\pi v d^3}{12l},\tag{5}$$

where v is the velocity of the Cs atoms. To improve the vacuum in the oven chamber, we add a thin copper tube with an inner diameter of 6 mm and a length of 80 mm by connecting it to the back side of the nipple. The vacuum pressure in the oven chamber is given by:

$$P_1=\frac{C_1}{C_1+C_{\text{pump1}}}P_0\approx\frac{C_1}{C_{\text{pump1}}}P_0.\tag{6}$$

This approximation is valid because $C_{\text{pump1}}=$ 50 L/s for the 50 L/s ion pump is much larger than $C_1=0.027$ L/s. C_1 is determined using the equation $1/C_1=1/C_{\text{nipple}}+1/C_{\text{pole}}+1/C_{\text{tube}}$, where C_{nipple}, C_{pole}, and C_{tube} are the conductance of the nipple, pole in the right flange of the nipple, and copper tube after the nipple, respectively. The theoretical vacuum pressure in the oven chamber is $P_1=2.42\times10^{-8}$ Pa, but the measured value is 3.6×10^{-9} Pa when the Cs atomic source is heated to 60 ℃. The large difference between theory and measurement is mainly attributed to the lower vacuum pressure in the cold nipple. Because a large number of heated Cs atoms condense on the inner wall of the nipple tube, the actual vacuum pressure is lower than the theoretical calculation based on the saturated vapor pressure of Cs atoms. The conductance of the Zeeman slower is given by $C_2=0.02284$ L/s. Considering the differential pressure induced by the Zeeman slower tube, the vacuum pressure P_2 in the science chamber is lower than P_1. The theoretical pressure is $P_2=3.7\times10^{-9}$ Pa, but the measurement indicates a lower value of 1.8×10^{-9} Pa.

3 Experimental measurement

In our vacuum system, the vacuum pressure in the oven chamber is mainly affected by the controlled temperature of the designed nipple because a differential pumping tube is installed between the nipple and oven chamber. We measured the effect of nipple temperature on the vacuum pressure in the oven chamber, as shown in Fig. 3. A lower nipple temperature is preferable to obtain a better vacuum in the oven chamber and therefore to achieve an ultrahigh vacuum in the science chamber. Based on the temperature of the nipple and the calculated vacuum differential pressure, we obtained the theoretical dependence of the vacuum pressure in the oven chamber on the temperature of the designed nipple. In Fig. 3, the theoretical calculation agrees with the measured values except for the data corresponding to the low temperature of $T=10$ ℃.

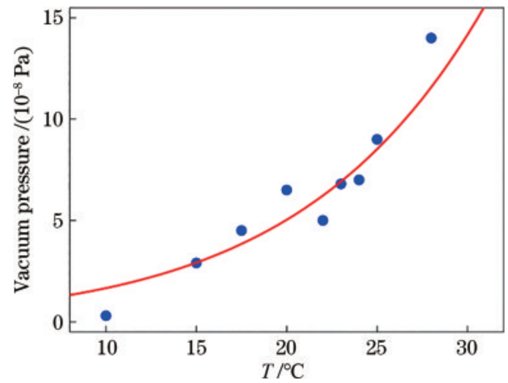

Fig. 3 Vacuum pressure in the oven chamber as a function of the controlled temperature for the nipple (the red line is from theoretical calculation)

We measured the variation in the magnetic field along the centerline of the Zeeman slower tube using a Gaussian meter. The dependence of the axial magnetic field on position is shown in Fig. 4. We numerically simulated a parabolic magnetic field using the designed coil structure and currents, and the measurements agreed with the simulation. Detuning of the saturated slowing laser is optimized by monitoring the fluorescence of the Cs MOT. According to Eq. (3), we calculated the theoretical variation in the magnetic field in the Zeeman slower with an efficiency of $\eta=0.85$. As shown in Fig. 4, the numerical simulation agrees with the measured results, whereas the difference from the theoretical curve on the sides is attributed to the limit of the sudden drop in the real magnetic field.

The atoms in the oven are heated to 60 ℃ and then ejected after the collimation of the nipple. High-flux atomic beams are slowed by the Zeeman slower. The atoms that enter the science chamber are captured by the MOT. The MOT consists of six cooling lasers, one repumping laser, and a pair of anti-Helmholtz coils. Each cooling laser is detuned by $\Delta_{\text{cool}}=-15$ MHz from the $6S_{1/2}, F=4\rightarrow 6P_{2/3}, F'=5$ cycling transition of the Cs atoms, and has a power of $P_{\text{cool}}=6$ mW. A

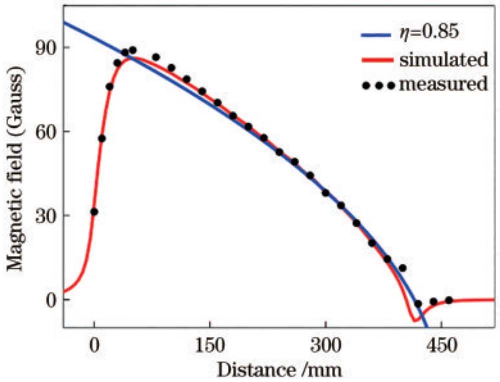

Fig. 4　A comparison between the simulated (red line) and measured (black dots) variations of the axial magnetic field in the Zeeman slower tube with the position by using the parameters shown in Fig. 2. A theoretical calculation (blue line) is presented with the efficiency of Zeeman slower $\eta = 0.85$

repumping laser with the power of 3.5 mW is detuned by $\Delta_{rep} = -10$ MHz from the $6S_{1/2}, F = 3 \rightarrow 6P_{2/3}, F' = 4$ transition. The coils operate at a current of $I = 8$ A, and the magnetic-field gradient is $\partial B/\partial Z = 13$ G/cm. We investigated the effect of detuning the slow laser on the number of cold Cs atoms in the MOT. Figure 5 shows the variation in the number of atoms loaded in the MOT with detuning of the slowing laser. The optimized detuning is $\delta = -93$ MHz. Using the optimized experimental parameters, we obtained 4×10^8 Cs atoms at a temperature of 80 μK in the MOT.

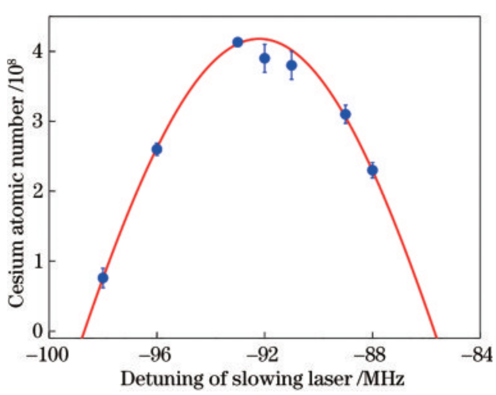

Fig. 5　Dependence of the number of Cs atoms in MOT on the detuning of slowing laser (each point is an average of five measurements, solid line is the Gaussian fit for the guide to the eye)

4　Conclusions

We present an ultrahigh-vacuum apparatus to slow down and trap Cs atoms. The designed cold nipple and differential pumping copper tube are placed between the oven and oven chamber to maintain a large differential pressure between the atomic source and the oven chamber. The low pressure of $\sim 3.6 \times 10^{-9}$ Pa achieved in the oven chamber is analyzed theoretically, and the effect of the temperature of the designed nipple on the vacuum pressure in the oven chamber is also investigated. The analysis and measurement of the Zeeman slower laser are provided in detail, and the detuning of the slowing laser is optimized to obtain a large number of atoms in the MOT. Our vacuum apparatus has advantages. First, it can be directly used to overcome the limit of the Cs atomic saturated vapor pressure on the vacuum degree in the oven chamber and make it easier to maintain an ultrahigh vacuum in the science chamber. Second, it extends the lifetime of the ion pump close to the oven by accumulating active Cs atoms in the cold nipple. Finally, this study provides a method for creating atomic BEC in a single vapor-loaded chamber for many atomic species.

References

[1] Luo X Y, Zou Y Q, Wu L N, et al. Deterministic entanglement generation from driving through quantum phase transitions[J]. Science, 2017, 355(6325): 620-623.

[2] Bloch I. Quantum coherence and entanglement with ultracold atoms in optical lattices[J]. Nature, 2008, 453 (7198): 1016-1022.

[3] Dai H N, Yang B, Reingruber A, et al. Generation and detection of atomic spin entanglement in optical lattices [J]. Nature Physics, 2016, 12(8): 783-787.

[4] Hu J Z, Feng L, Zhang Z D, et al. Quantum simulation of Unruh radiation[J]. Nature Physics, 2019, 15(8): 785-789.

[5] Li Y Q, Zhang J H, Wang Y F, et al. Atom-optically synthetic gauge fields for a noninteracting Bose gas[J]. Light: Science & Applications, 2022, 11: 13.

[6] Wang Y F, Zhang J H, Li Y Q, et al. Observation of interaction-induced mobility edge in an atomic Aubry-André wire[J]. Physical Review Letters, 2022, 129(10): 103401.

[7] Ludlow A D, Boyd M M, Ye J, et al. Optical atomic clocks[J]. Reviews of Modern Physics, 2015, 87(2): 637.

[8] Lücke B, Scherer M, Kruse J, et al. Twin matter waves for interferometry beyond the classical limit[J]. Science, 2011, 334(6057): 773-776.

[9] Kong D H, Wang Z H, Guo F, et al. A transportable optical lattice clock at the National Time Service Center [J]. Chinese Physics B, 2020, 29(7): 070602.

[10] Wang Y F, Du H Y, Li Y Q, et al. Testing universality of Feynman-Tan relation in interacting Bose gases using high-order Bragg spectra[J]. Light: Science & Applications, 2023, 12: 50.

[11] Zhang J Y, Chen L L, Cheng Y A, et al. Movable precision gravimeters based on cold atom interferometry [J]. Chinese Physics B, 2020, 29(9): 093702.

[12] Marti G E, Olf R, Vogt E, et al. Two-element Zeeman slower for rubidium and lithium[J]. Physical Review A, 2010, 81(4): 043424.

[13] Hopkins S A, Butler K, Guttridge A, et al. A versatile dual-species Zeeman slower for caesium and ytterbium[J]. Review of Scientific Instruments, 2016, 87(4): 043109.

[14] Phillips W D, Metcalf H. Laser deceleration of an atomic beam[J]. Physical Review Letters, 1982, 48(9): 596-599.

[15] Dieckmann K, Spreeuw R J C, Weidemüller M, et al. Two-dimensional magneto-optical trap as a source of slow atoms[J]. Physical Review A, 1998, 58(5): 3891-3895.

[16] Tiecke T G, Gensemer S D, Ludewig A, et al. High-flux two-dimensional magneto-optical-trap source for cold lithium atoms[J]. Physical Review A, 2009, 80(1): 013409.

[17] Götz S, Höltkemeier B, Hofmann C S, et al. Versatile cold atom target apparatus[J]. Review of Scientific Instruments, 2012, 83(7): 073112.

[18] Streed E W, Chikkatur A P, Gustavson T L, et al. Large atom number Bose-Einstein condensate machines [J]. Review of Scientific Instruments, 2006, 77(2): 023106.

[19] Modugno G, Ferrari G, Roati G, et al. Bose-Einstein condensation of potassium atoms by sympathetic cooling [J]. Science, 2001, 294(5545): 1320-1322.

[20] Weber T, Herbig J, Mark M, et al. Bose-Einstein condensation of cesium[J]. Science, 2003, 294(5604): 232-235.

[21] Bowden W, Gunton W, Semczuk M, et al. An adaptable dual species effusive source and Zeeman slower design demonstrated with Rb and Li[J]. Review of Scientific Instruments, 2016, 87(4): 043111.

[22] Paris-Mandoki A, Jones M D, Nute J, et al. Versatile cold atom source for multi-species experiments[J]. Review of Scientific Instruments, 2014, 85(11): 113103.

[23] Foot C J. Atomic physics[M]. New York: Oxford University Press, 2005: 181.

[24] Dedman C J, Nes J, Hanna T M, et al. Optimum design and construction of a Zeeman slower for use with a magneto-optic trap[J]. Review of Scientific Instruments, 2004, 75(12): 5136-5142.