Transport of Bose-Einstein condensate in QUIC trap and separation of trapping spin states

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Abstract: We have studied the locomotion track of ^{87}Rb Bose-Einstein condensate during decompressing the trap into the center of the glass cell in a quadrupole-Ioffe configuration trap. In order to change the position of the BEC, the current in the quadrupole coils is reduced while the current in the Ioffe coil keeps constant. Because of the strongly reduced trap frequencies of the moved trap, the BEC considerably sags down due to the gravity. Thus an inflexion point exists in the process of moving BEC. When rubidium atoms go over the inflexion point, they cannot keep in balance under the gravity and the force provided by a magnetic field, and flow downward and towards Ioffe coil. By utilizing this effect, the trapped atoms with the spin state $|F=2, m_F=1\rangle$, which are left over in the BEC, can be separated from the BEC of $|F=2, m_F=2\rangle$ state.

OCIS codes: (020.1475) Bose-Einstein condensates; (020.2930) Hyperfine structure.

References and links

1. Y. Miroshnychenko, D. Schrader, S. Kuhr,W. Alt, I. Dotsenko, M. Khudaverdyan, A. Rauschenbeutel, and D. Meschede, “Continued imaging of the transport of a single neutral atom,” Opt. Express **11**, 3498-3502 (2003).
2. W. Wohlleben, F. Chevy, K. Madison, and J. Dalibard, “An atom faucet,” Eur. Phys. J. D **15**, 237-244 (2001).
3. Z. T. Lu, K. L. Corwin, M. J. Renn, M. H. Anderson, E. A. Cornell, and C. E. Wieman, “Low-velocity intense source of stoms from a magneto-optical trap,” Phys. Rev. Lett. **77**, 3331-3334 (1996).
4. J. Arlt, O. Maragò, S. Webster, S. Hopkins, and C. J. Foot, “A pyramidal magneto-optical trap as a source of slow atoms,” Opt. Commun. **157**, 303-309 (1998).
5. A. B. Mundt, A. Kreuter, C. Becher, D. Leibfried, J. Eschner, F. Schmidt-Kaler, and R. Blatt, “Coupling a single atomic quantum bit to a high finesse optical cavity,” Phys. Rev. Lett. **89**, 103001 (2002).
6. L. Fallani, C. Fort, J. E. Lye, and M. Inguscio, “Bose-Einstein condensate in an optical lattice with tunable spacing: transport and static properties,” Opt. Express **13**, 4303-4313 (2005).
7. T. Schumm, S. Hofferberth, L. M. Andersson, S. Wildermuth, S. Groth, I. Bar-Joseph, J. Schmiedmayer, and P. Krüger, “Matter-wave interferometry in a double well on an atom chip,” Nature Physics **1**, 57-62 (2005).
8. T. L. Gustavson, A. P. Chikkatur, A. E. Leanhardt, A. Görlitz, S. Gupta, D. E. Pritchard, and W. Ketterle, “Transport of Bose-Einstein condensates with optical tweezers,” Phys. Rev. Lett. **88**, 020401 (2002)
9. S. Schmid, G. Thalhammer, K. Winkler, F. Lang, and J. H. Denschlag, “Long distance transport of ultracold atoms using a 1D optical lattice,” New J. Phys. **8**, 159 (2006)
10. R. Folman, P. Krüger, J. Schmiedmayer, J. Denschlag, and C. Henkel, “Microscopic atom optics: from wires to an atom chip,” Adv. At. Mol. Opt. Phys. **48**, 263-356 (2002)
11. H. Ott, J. Fortagh, G. Schlotterbeck, A. Grossmann, and C. Zimmermann, “Bose-Einstein condensation in a surface microtrap,” Phys. Rev. Lett. **87**, 230401 (2001)
12. C. Klempt, T. Henninger, O. Topic, J. Will, St. Falke, W. Ertmer, and J. Arlt, “Transport of a quantum degenerate heteronuclear Bose-Fermi mixture in a harmonic trap,” Eur. Phys. J. D **48**,121-126 (2008).

#119578 - $15.00 USD Received 6 Nov 2009; revised 30 Dec 2009; accepted 7 Jan 2010; published 14 Jan 2010

13. T. Esslinger, I. Bloch, and T. W. Hänsch, "Magnetostatic trapping fields for natural atoms," Phys. Rev. A **58**, R2664-R2267 (1998).
14. J. Weiner, V. S. Bagnato, S. Zilio, and P. S. Julienne, "Experiments and theory in cold and ultracold collisions," Rev. Mod. Phys. **71**, 1-85 (1999).
15. T. P. Meyrath, "Experiments with Bose-Einstein Condensation in an Optical Box" PhD Thesis (USA:THE UNIVERSITY OF TEXAS) (2005)
16. M.-S. Chang, C. D. Hamley, M. D. Barrett, J. A. Sauer, K. M. Fortier, W. Zhang, L. You, and M. S. Chapman, "Observation of Spinor Dynamics in optically trapped 87Rb Bose-Einstein condensates," Phys. Rev. Lett. **92**, 140403 (2004)
17. X. Ma, S. Chen, F. Yang, L. Xia, X. Zhou, Y. Wang, and X. Chen, "Observation of F = 2 spinor Bose-Einstein condensation in a magnetic field," Chin. Phys. Lett. **22**, 1106-1109 (2005)
18. D. Wei, D. Xiong, H. Chen, P. Wang, L. Guo, and J. Zhang, "Simultaneous Magneto-optical Trpping of Fermionic ^{40}K and Bosonic ^{87}Rb atoms," Chin. Phys. Lett. **24** 1541-1544 (2007).
19. D. Xiong, H. Chen, P. Wang, X. Yu, F. Gao, and J. Zhang, "Quantum Degenerate FermiCBose mixtures of ^{40}K and ^{87}Rb atoms in a Quadrupole-Ioffe configuration trap," Chin. Phys. Lett. **23**, 843-846 (2008).
20. T. Bergeman, G. Erez, and H. J. Metcalf, "Magnetostatic trapping fields for neutral atoms," Phys. Rev. A **35**, 1535-1546 (1987).
21. D. Xiong, P. Wang, Z. Fu, and J. Zhang, "Evaporative cooling rubidium atoms with microwave radiation," Chin. Opt. Lett. in press.
22. M. Hass, V. Leung, D. Frese, D. Haubrich, S. John, C. Weber, A. Rauschenbeutel, and A. Meschede, "Species-selective microwave cooling of a mixture of rubidium and caesium atoms," New J. Phys. **9**, 147 (2007).
23. C. Silber, S. Günther, C. Marzok, B. Deh, Ph. W. ourteille, and C. Zimmermann, "Quantum-degenerate mixture of fermionic lithium and bosonic rubidium gases," Phys. Rev. Lett. **95**, 170408 (2005).

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1. Introduction

Transport of ultracold atoms gas and the precise control of the position [1] have played a very important role in experiments, for instance, transferring the atoms in double magneto-optical trap [2, 3, 4], loading atoms into cavity for quantum computing [5], observing the dipole oscillations of the harmonically trapped condensates [6] in the presence of the lattice and the construction of interferometer for precision measurement [7]. Many different kinds of transport methods for the ultracold atoms over macroscopic distances have been studied, for instance, a moving dipole trap [8], optical lattice [9], chip trap [10, 11], transforming magnetic fields [12]. Among the different kinds of the magnetic trap to create a BEC, the QUIC (quadrupole-Ioffe configuration) trap [13] has been widely adopted in the experiment due to its simple structure and low power dissipation. The QUIC trap consists of a pair of anti-Helmholtz coils and a third coil in perpendicular orientation, in which the ultracold atoms are close to the Ioffe coil. Thus the optical access is limited because the atoms are far from the geometric center of vacuum cell. So it is desirable to transport the sample to a favorable position for some experiments, such as the research of BEC spin dynamics in 3D lattice and the manipulation of cold atoms in the vicinity of Feshbach resonance [14]. This transport of BEC in the QUIC trap can be realized by reducing the current in the quadrupole coils while keeping the current in the Ioffe coil [12, 15].

In this paper, we report the direct observation of the locomotion track of BEC from their initial position in a QUIC trap to the geometric center of the glass cell. Due to the gravity sag and the character of quadrupole-Ioffe configuration trap, an inflexion exists in the locomotion track. For the ^{87}Rb ground state, the $|F, m_F\rangle$ states $|2,2\rangle$ and $|2,1\rangle$ are low field seeking states and may be trapped. Due to different trap frequencies for different spin states, the trap states $|2,2\rangle$ and $|2,1\rangle$ present different locomotion tracks and inflexion points. This effect may be used for separating the different trap spin states. This method doesn't need an additional bias magnetic field to produce the magnetic gradient for separating the spin states [16, 17], and presents the large spacial distance between the separated trap spin components. The distance between ^{87}Rb in the $|F = 2, m_F = 2\rangle$ state and in the $|F = 2, m_F = 1\rangle$ state is up to 1.624 mm in the horizontal direction. The separated spin states still stay in magnetic harmonic potential, which are very useful for further experiments. By utilizing this effect, we observe the trapping

#119578 - $15.00 USD Received 6 Nov 2009; revised 30 Dec 2009; accepted 7 Jan 2010; published 14 Jan 2010

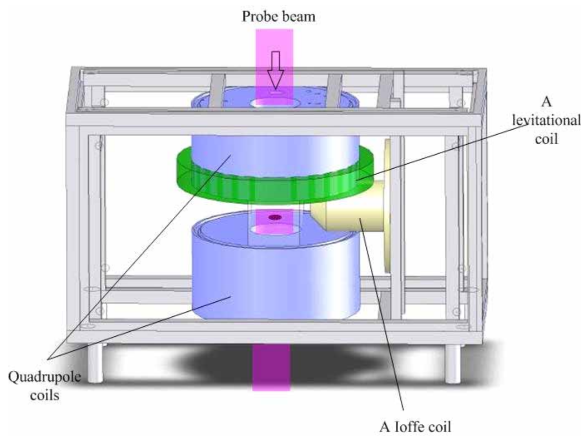

Fig. 1. Schematic of the experimental apparatus showing the QUIC trap setup and a levitation coil.

atoms with the spin state $|F = 2, m_F = 1\rangle$, which are residual in the BEC of $|F = 2, m_F = 2\rangle$ state.

2. Experimental setup

Our experimental apparatus is based on double magneto-optical trap (MOT) apparatus, which has been described in detail previously [18, 19]. Figure 1 shows our experimental setup for magnetic trap, which consists of an Ioffe-Pritchard potential produced by three coils in Quadrupole-Ioffe configuration (QUIC) [13]. To compensate the gravitational effect during moving the sample from initial QUIC position to the center of glass cell by lowering the current passing through quadrupole coils and keeping the current in the Ioffe coil, a levitating field provided by a leviation coil is used [12, 15]. The atomic sample is detected by the time of flight absorption image and the probe beam used for absorption imaging passes through the glass cell in the vertical direction (gravity axis) as shown in Fig. 1.

3. Experimental results

3.1. Transferring the atoms into the center of glass cell

After optical pumping in MOT 2, cold rubidium atoms are moved towards Ioffe coil about 12 mm from quadrupole potential center and trapped in the QUIC trap. At this stage, the current though three coils is 32 A and the magnetic trap is an Ioffe-Prichard type with a harmonic potential in the center and no zero magnetic field, which is suitable for evaporative cooling. After ultracold atomic sample is prepared by RF evaporative cooling, we move the quantum degenerate gas back to the center of the glass cell by reducing the current in the quadrupole coils while keeping the current in the Ioffe coil. Because the trap is weaker and weaker when we lower the current through quadrupole coils, gravity is strong enough to pull the trap center down. Thus an inflexion point exists in the process of moving BEC, which can not reach the center of the glass cell. In order to shifting QUIC trap back to the center of glass cell, a vertically oriented levitation coil is necessary to counteract the gravity. When the quadrupole current is gradually ramped down to 10 A and the levitation coil is with the current of 1.5 A, the sample is adiabatically transported to the geometric center of glass cell with 3 seconds.

#119578 - $15.00 USD Received 6 Nov 2009; revised 30 Dec 2009; accepted 7 Jan 2010; published 14 Jan 2010

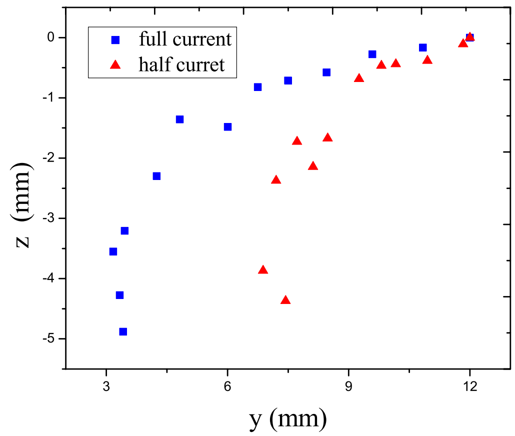

Fig. 2. The locomotion track of ^{87}Rb atoms in spin $|F=2,m_F=2\rangle$ state during decompressing the trap into the center of the glass cell without the levitating field. The curves with square and trigonal dots are the initial current with 32 and 16 A through the QUIC coils respectively.

3.2. Track of BEC without a levitating field.

We measure the track of the BEC of $|F=2,m_F=2\rangle$ state during decompressing Ioffe trap without the levitating field. As shown in Fig. 2, the initial position of QUIC trap is the point (y,z)=(12 mm, 0 mm). The sample will move towards the center of the glass cell at the beginning of the decompressing QUIC trap, and the position of the sample drop a little in z-direction due to the strong trap frequencies. As the current though qudrupole coils continually ramps down, the position in z-direction gradually deviates from the axial line of Ioffe coil (y-direction). The effect that gravity pulls down the trap center will be more and more obvious. When the inflexion point appears, in which the sample will not move towards the center of glass cell, but opposite direction, although we still lower the current though quadrupole coils. We measure the locomotion tracks of the BEC of $|F=2,m_F=2\rangle$ state with two different initial conditions - different trap frequencies. One curve with square dot is initial current with 32 A through the QUIC coils (Ioffe coil and quadrupole coils), the other with trigonal dot 16 A.

The track of the sample is detected by absorption imaging. Since the probe beam is antiparallel to the z-axis direction (the abscissa axis is y-axis direction), the position of the sample moved in y-direction can be directly obtained from the absorption image. For determining the position of the sample in z-direction, a little trick is used. We measure the free-fall time between the initial position and the final position where atom sample collides with the wall of the cell by time of flight absorption image. After the atoms collide with the cell wall, there is no longer any absorption signal. Then we use the formula $s=gt^2/2$ to calculate the position of the atomic sample in z-direction, where g is acceleration due to gravity.

4. Numerical analysis and explanation

We present the explanation for this phenomenon by numerical calculation, which bases on the formulas[20]. For a single coil with radius R perpendicular to the z axis and centered at $z=A$,

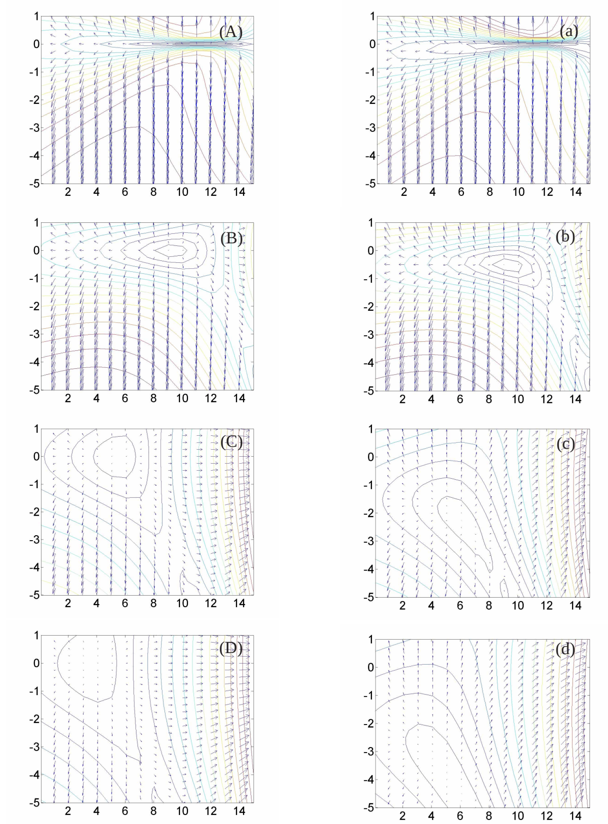

Fig. 3. The contour and vector plots of the gradient field in yz-plane during ramping down the current though quadrupole coils. (A), (B), (C), and (D) show the gradient field without considering the effect of gravity and with constant Ioffe current 32 A and the quadrupole current of 32, 24, 16, 13.5 A respectively. (a) to (d) are the case considering the gravity sag for ^{87}Rb in the state $|F=2, m_F=2\rangle$.

the transverse ρ and axial z components of the magnetic field with the current I are given by

$$B_z = \frac{\mu I}{2\pi} \frac{1}{[(R+\rho)^2+(z-A)^2]^{1/2}} [K(k^2) + \frac{R^2-\rho^2-(z-A)^2}{(R-\rho)^2+(z-A)^2} E(k^2)] \tag{1}$$

$$B_\rho = \frac{\mu I}{2\pi\rho} \frac{z-A}{[(R+\rho)^2+(z-A)^2]^{1/2}} [-K(k^2) + \frac{R^2+\rho^2+(z-A)^2}{(R-\rho)^2+(z-A)^2} E(k^2)] \tag{2}$$

where

$$k^2 = \frac{4R\rho}{(R+\rho)^2+(z-A)^2} \tag{3}$$

$$\rho = \sqrt{x^2+y^2} \tag{4}$$

and $K(k^2)$ and $E(k^2)$ are the complete elliptic integrals. For a vacuum, in SI units (amps, meters, tesla), $\mu = \mu_0 = 4\pi \times 10^{-7}$. Thus the force due to magnetic trap (corresponding magnetic gradient field) is

$$F(r) = -\nabla U(r) = -g_F m_F \mu_B \nabla B(r) \tag{5}$$

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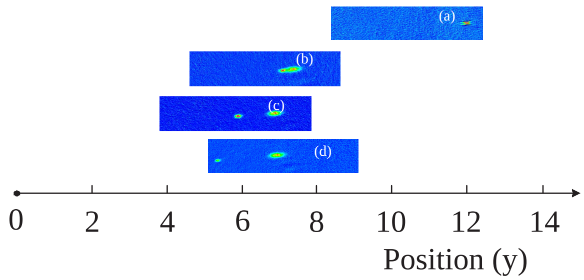

Fig. 4. Absorption images of ^{87}Rb atoms in F=2 spin state with 1 ms expansion time using MW radiative evaporative cooling. Due to the gravity sag and the character of quadrupole-Ioffe configuration trap, ^{87}Rb atoms in the $|F=2,m_F=1\rangle$ state is separated from them in the $|F=2,m_F=2>$ state during decompressing the Ioffe trap without a levitating field.

where $r=\sqrt{x^2+y^2+z^2}$, g_F is landé factor for the different spin states, B(r) is the modulus of the magnetic field and U(r) is the trap potential. We plot the gradient field for different quadrupole currents with constant Ioffe current 32 A, as shown in Fig. 3. First we consider the Rb atoms in QUIC trap with quadrupole and Ioffe coils current of 32 A without gravity effect. Fig. 3(A) presents the gradient field in yz-plane (containing Ioffe and quadrupole coils axes). It is obvious that the minimum of the QUIC trap locates in the abscissa axis. For ^{87}Rb in ground-state hyperfine state $|F=2,m_F=2\rangle$, the gradient of the magnetic field needs to be 15.2427 G/cm in order to compensating the gravity. Thus gravity will pull down the trap center a little in z-direction (Figs. 3(a)). From these two figures, we hardly find the difference of the gradient field due to the strong magnetic trapping whether we consider gravity or not. When we continue to ramp down the quadrupole current, the difference of the gradient field will be obvious. When we reduce the current through quadrupole coils, the balance point (the trapping position for atoms) will move towards the quadrupole center, at the same time, gradually fall off the Ioffe axial line in the z-direction with considering the gravity. Moreover, it moves more slowly in y-direction comparing to the case without the gravity. Thus the balance point will lag the minimum of magnetic field (without the gravity) in y-direction, and the distance between them will be larger and larger. The distance can be up to 1.75 mm when the current through quadrupole coils is 13.5 A. At this stage, we hardly find the balance point in the gradient field of QUIC trap (Fig. 3(d)), and the atomic sample will flow downward and towards Ioffe coil (following the minimum of the gradient field) and lose quickly.

From the Eq. (5) we know that the force (z-direction) in QUIC trap for ^{87}Rb in ground-state hyperfine state $|F=2,m_F=2\rangle$ is twofold larger than it for ^{87}Rb in ground-state hyperfine state $|F=2,m_F=1\rangle$. Thus we can conclude that the track of ^{87}Rb atoms in the $|F=2,m_F=2\rangle$ state with initial current 16 A (Fig. 2) can stand for the track of ^{87}Rb atoms in the $|F=2,m_F=1\rangle$ state with initial current 32 A. In the other words, Fig. 2 may demonstrate theoretically that the ^{87}Rb atoms in state $|F=2,m_F=1\rangle$ and in state $|F=2,m_F=2\rangle$ will separate in space during decompressing Ioffe trap into the glass center without the levitation field.

5. An application of the separation of the spin states

In our experiment the ^{87}Rb atoms are prepared in the ground-state hyperfine state $|F=2,m_F=2\rangle$, which are the low-field seeking state. We utilize two methods to perform evaporative cooling: radio-frequency (RF), microwave (MW) techniques [21]. The MW-knife is tuned to the hyperfine transition at 6.8 GHz, which induces transitions from trapped $|F=2,m_F=2\rangle$ state

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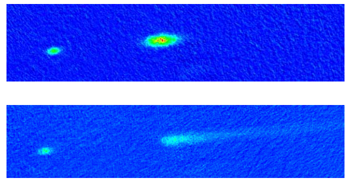

Fig. 5. The comparison of ^{87}Rb atomic sample loss in the $|F=2, m_F=1\rangle$ state before and after its inflexion point. These absorption pictures are taken with 1 ms expansion time.

to untrapped $|F=1, m_F=1\rangle$ state. When the rubidium atoms are cooled down to critical temperature point, a lot of rubidium atoms are pumped back into the trapping $|F=2, m_F=1\rangle$ state from the $|F=1, m_F=1\rangle$ state by the same MW radiation in the course of evaporation [22, 23]. With RF-induced evaporative cooling, the spin of the left atoms in the trap is almost in the $|F=2, m_F=2\rangle$ state, and only a little atoms stay in the $|F=2, m_F=1\rangle$ state [21]. However, with MW radiative evaporative cooling, almost half of atoms stay in the $|F=2, m_F=1\rangle$ state [21]. After using microwave evaporative cooling, we decompress the QUIC trap without adding levitating field. As predicted, ^{87}Rb atomic sample move towards the quadrupole field center when we decrease the quadrupole current. Meanwhile, a novel phenomenon, that ^{87}Rb atoms sample is separated into two part, is observed as shown in Fig. 4. This demonstrates that some ^{87}Rb atoms stay in the ground-state hyperfine state $|F=2, m_F=1\rangle$ after microwave evaporation cooling. And ^{87}Rb atoms in the $|F=2, m_F=2\rangle$ state and in the $|F=2, m_F=1\rangle$ state are separated in space when reducing the quadrupole current. The distance becomes the largest about 1.624 mm in y-direction (as shown in Fig. 4) when the quadrupole current ramps down to 17.3 A from initial current 32 A. At this point, the ^{87}Rb atomic sample in the state $|F=2, m_F=1\rangle$ reaches its inflexion point. It demonstrated that this is a simple and useful method to separate the spin states. It doesn't need an additional bias magnetic field to produce the magnetic gradient for separating the spin states, and presents the large spacial distance between the separated trap spin components. The separated trapping spin states still stay in magnetic harmonic potential, which can be used for further experiments. If we lower the quadrupole current a little continuously at the inflexion point, the ^{87}Rb atoms in the $|F=2, m_F=1\rangle$ state will lose quickly from magnetic trap. In order to proving this, we let the atomic sample reside 200 ms in magnetic trap after ramping down quadrupole current to the values of before and after the inflexion point of the $|F=2, m_F=1\rangle$ state as shown in Fig. 5(a) and Fig. 5(b) respectively. In this process, the ^{87}Rb atoms in the $|F=2, m_F=2\rangle$ state are purified because the ^{87}Rb atoms in the $|F=2, m_F=1\rangle$ state are removed automatically.

6. Conclusion

In conclusion, we have directly observed the locomotion track of ultracold ^{87}Rb atoms in decompressing Ioffe trap without the levitating field. Due to the gravitional sag and the characteristic of quadrupole-Ioffe configuration trap, an inflexion point exists in the locomotion track. By utilizing this effect, ^{87}Rb in different spin state can be separated effectively in space. For the first time to our knowledge, the locomotion track of ultracold atoms in decompressing Ioffe trap and the separation of the different trapping spin states were observed experimentally. Comparing to other methods, an additional bias magnetic field is not needed to produce the magnetic gradient for separating the spin states. Because the separated atoms are still in the harmonic potential field, it will provide an opportunity for further operating ultracold atoms.

This research was supported in part by NSFC for Distinguished Young Scholars (Grant No.

10725416), National Basic Research Program of China (Grant No. 2006CB921101), NSFC Project for Excellent Research Team (Grant No. 60821004), NSFC (Grant No. 60678029), and the TYMIT and TSTIT of Shanxi.

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