Novel Optical Trap of Atoms with a Doughnut Beam

Takahiro Kuga, Yoshio Torii, Noritsugu Shiokawa, and Takuya Hirano
Institute of Physics, University of Tokyo, 3-8-1 Komaba, Meguro-ku Tokyo 153, Japan

Yukiko Shimizu and Hiroyuki Sasada
Department of Physics, Faculty of Science and Technology, Keio University, 3-14-1 Hiyoshi, Kohoku-ku Yokohama 223, Japan

(Received 28 February 1997)

We have constructed a novel optical trap for neutral atoms by using a Laguerre-Gaussian (doughnut) beam whose frequency is blue detuned to the atomic transition. Laser-cooled rubidium atoms are trapped in the dark core of the doughnut beam with the help of two additional laser beams which limit the atomic motion along the optical axis. About 10^8 atoms are initially loaded into the trap, and the lifetime is 150 ms. Because the atoms are confined at a point in a weak radiation field in the absence of any external field, ideal circumstances are provided for precision measurements. The trap opens the way to a simple technique for atom manipulation, including Bose-Einstein condensation of gaseous atoms. [S0031-9007(97)03456-X]

PACS numbers: 32.80.Pj, 39.90.+d

Since the first successful laser cooling of neutral atoms in 1985 [1], various techniques have been proposed and demonstrated to slow the atomic motion and to increase the atomic density. A magneto-optical trap (MOT) provides an easy way to prepare a cold (~mK) and dense ($\sim 10^{11}$ cm^{-3}) atomic cloud [2], and polarization gradient cooling (PGC) achieves the sub-Doppler temperature [3]. Subsequently, Raman cooling and velocity-selective coherent population trapping further cool the atoms below the photon-recoil limit [4,5]. Subsequent evaporative cooling of the atoms in a magnetic trap finally realizes Bose-Einstein condensation (BEC) of a dilute atomic system [6]. Considerable efforts have also been made to trap atoms and to increase their phase space density in an all-optical method [7–9]. An inverted pyramid trap confined 4.5×10^5 sodium atoms with the aid of gravity, and subsequent Raman cooling increased the phase space density by a factor of 320, which was still 400 times smaller than that required for BEC [9].

In experimental research on laser cooling, Gaussian laser beams have been exclusively employed so far. Recently, Laguerre-Gaussian (LG) optical beams have attracted attention for two reasons. First, the LG_{pl} beams possess orbital angular momentum along the optical axis when l is not zero, where p and l are the radial and azimuthal indices of the LG modes [10]. It has been demonstrated that a macroscopic absorptive particle is rotated by angular momentum transfer from the LG beams [11], and laser cooling of trapped ions with the LG beams has been theoretically discussed [12]. Second, the $\mathrm{LG}_{pl\neq 0}$ beams have a spiral phase structure, hence the phase is undefined on the optical axis, where radiation intensity must be zero [13]. A certain class of LG beams, $\mathrm{LG}_{0l\neq 0}$, is called a doughnut beam because in cross section a dark spot is enclosed by a bright ring. This intensity distribution, in conjunction with the optical dipole force, provides a line of potential extrema along the optical axis. The potential has already been utilized in a trap for a macroscopic dielectric particle that has a lower refractive index than surrounding materials at the radiation wavelength [14].

In this Letter, we report on a novel trap using the LG laser beam. The trap is able to store 10^8 rubidium atoms, which is the largest number ever obtained by optical dipole traps. Furthermore, it requires no magnetic field and confines the atoms at the point of the minimum optical field strength. Therefore, it has great advantages over most of the conventional traps with Gaussian beams, especially for precision measurement applications which require minimum internal level shifts induced by external fields.

We evaluated the dipole force of the novel optical trap for a rubidium atom in the LG_{0l} doughnut beam blue detuned to the D2 transition. The potential energy of the induced dipole force is written by [15]

$$U(r) = \frac{\hbar\delta_c}{2} \ln\left[1 + \frac{I(r)/I_0}{1 + (2\delta_c/\Gamma)^2}\right], \qquad (1)$$

where $\delta_c = \omega_l - \omega_0$ is the detuning between the laser frequency ω_l and the atomic transition ω_0, I_0 is the saturation intensity, and Γ is the natural linewidth of the atomic transition. The intensity distribution of the doughnut beam is given by

$$I(r) = P\,\frac{2^{l+1} r^{2l}}{\pi l!\, r_0^{2(l+1)}} \exp[-2r^2/r_0^2]. \qquad (2)$$

Here, P and r_0 are the power and radius of the LG_{0l} beam. Figure 1 shows the calculated trapping potential in the plane perpendicular to the optical axis of the LG_{03} beam. The parameters in Eqs. (1) and (2) take the values of $I_0 = 2$ mW/cm^2, $\Gamma = 6$ MHz, $\delta_c = 60$ GHz, $P = 600$ mW, and $r_0 = 600$ μm. From this, we obtain the potential barrier of about 40 μK, which is high enough to trap the rubidium atoms cooled to about 10 μK by PGC.

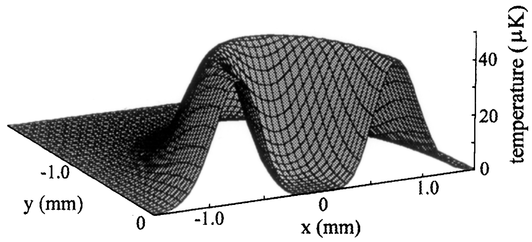

FIG. 1. Cross section of the calculated trapping potential formed by the LG_{03} beam in the plane perpendicular to the optical axis.

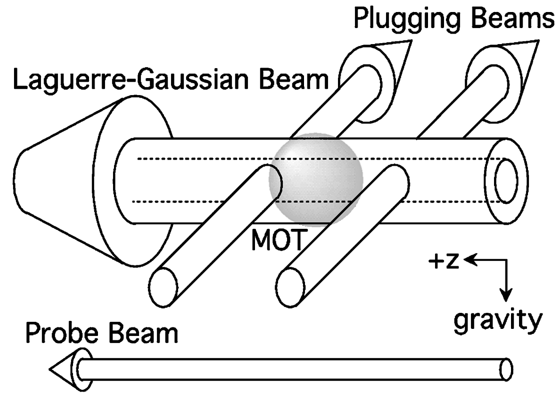

FIG. 2. Schematic illustration of the novel optical trap.

We constructed a standard vapor-cell MOT [16] to trap ^{85}Rb atoms. A cell was pumped by a turbo pump and an ion pump, and the pressure was typically 10^{-7} Pa. Two external-cavity diode lasers were used for cooling and repumping the atoms. The cooling laser was tuned 17 MHz below the $5S_{1/2}(F = 3) - 5P_{3/2}(F' = 4)$ transition, and the repumping laser was resonant with the $5S_{1/2}(F = 2) - 5P_{3/2}(F' = 3)$ transition. The diameter and intensity of the cooling laser were 10 mm and 10 $\mathrm{mW/cm^2}$, and those of the repumping beam were 15 mm and 3 $\mathrm{mW/cm^2}$. The diameter of the MOT was 1.5 mm, and the number and temperature of the trapped atoms were determined to be 3×10^8 and 150 μK by a time-of-flight (TOF) method [3]. The TOF signal was provided by a probe laser beam with a diameter of 0.4 mm propagating 7 mm below the MOT. The distance between the probe beam and MOT was far enough that the initial spatial distribution of the trapped atoms did not significantly influence the TOF signal.

An LG beam was generated from a Hermite-Gaussian (HG) beam [17], which was produced by a Ti:sapphire (TS) laser pumped by an all-line Ar-ion laser. The TS laser consisted of a four-mirror bow-tie cavity, a birefringent filter, an optical diode, and a thin etalon, and oscillated at a single frequency of a few-tens-megahertz linewidth. A tungsten wire of 20 μm diameter was inserted into the laser cavity, and the position was adjusted to generate the HG_{03} laser beam. It was converted to the LG_{03} mode by an astigmatic mode converter, which was composed of a pair of cylindrical lenses (focal length: $f = 25$ mm) separated by a distance of $d = \sqrt{2} f$.

A schematic illustration of the novel optical trap is shown in Fig. 2. Precooled atoms are trapped in the dark core of the doughnut beam (2D trap). Because there is no restoring force along the z axis, we add two "plugging" laser beams to make the three-dimensional optical trap (3D trap). To generate the plugging beams, we recycle the doughnut beam which is divided into two beams and redirected to the trap with a separation of 2 mm. The doughnut beam is 1.5 mm in diameter, and the plugging beam 0.7 mm. Thus the plugging beam provides a higher potential barrier than the doughnut beam.

The procedure for constructing the novel trap was as follows. Rubidium atoms were first trapped by MOT and further cooled to 10 μK by PGC, which was achieved by (i) switching off the magnetic field for MOT quickly (less than 1 ms), (ii) gradually increasing the cooling laser detuning from -17 to -80 MHz in 15 ms, (iii) reducing the cooling laser intensity to one-tenth of the initial intensity, and (iv) waiting about 3 ms. Subsequently, the PGC laser beams were turned off, and the doughnut beam was immediately introduced into the atomic cloud by opening a mechanical shutter within 1 ms. The atoms were then stored in the novel trap.

We used the TOF technique to examine performance of the novel trap. After a certain period of trapping, the atoms were released by shutting off the doughnut beam, and the falling atoms were detected as absorption of the probe laser beam. We obtained the largest TOF peak when the doughnut beam detuning was $+57$ GHz to the ^{85}Rb $5S_{1/2}(F = 3) - 5P_{3/2}(F' = 4)$ transition with the maximum available power of 600 mW. Figure 3 shows the TOF signals of the 2D and 3D traps under this condition. Individual signals were obtained by varying the trapping time, and the origin of the time axis corresponds to the instant when the trapping beams were turned on. The first TOF peak is due to the atoms not trapped by the novel trap; the second, to trapped atoms. An asymmetric shape of the first peak is presumably due to heating and pushing of the untrapped atoms by the trapping beams. The single TOF peak of zero trapping time corresponds to the atoms initially trapped in the MOT.

We can deduce the number and temperature of the trapped atoms from the peak height and width of the TOF signal. Figure 4 shows the decay of the number of the trapped atoms as a function of the trapping time. The lifetime of the 3D trap was determined to be 150 ms. The decay of the 2D trap was faster than that of the 3D trap and did not fit a simple exponential function. By extrapolating the decay line to zero trapping time, we can estimate that one-third of the atoms in the MOT is initially loaded in the novel trap. Hence the absolute number is about 10^8. The temperature of the trapped atoms was approximately 18 μK and almost independent of the trapping time.

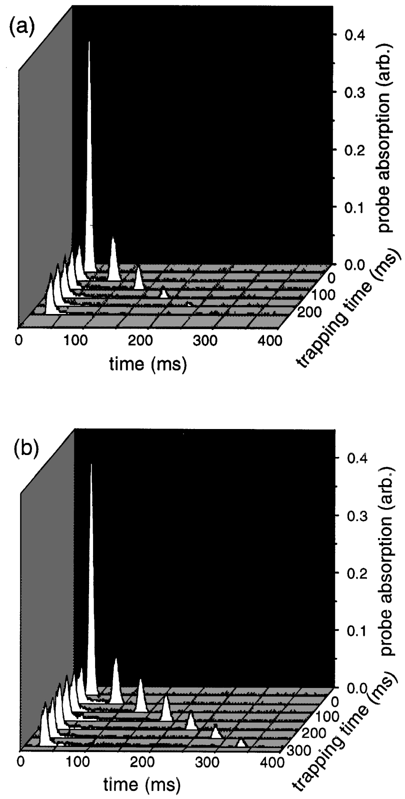

FIG. 3. TOF signal for the 2D (a) and 3D (b) optical traps. Individual traces are obtained by varying the trapping time.

We considered four factors limiting the lifetime of the novel trap: (i) radiation pressure which accelerates the atoms towards the $+z$ direction, (ii) heating by random photon scattering, (iii) drift along the z axis due to the initial distribution of the atomic velocity, and (iv) collisions with the background gas. The effects of (iii) and (iv) are not important in the present case because the atoms cooled down to 10 μK drift only a few millimeters in 200 ms and the collision rate at the present pressure is on the order of 0.1 s^{-1}. To evaluate the contributions of (i) and (ii), we removed one of the plugging laser beams from the 3D trap. Removing the laser beam plugging the hole of the upper stream of the doughnut beam does not have any significant effects. In contrast, when the other hole was opened, the observed TOF signals changed remarkably and became the same as those of the 2D trap. These results suggested that the lifetime of the 2D trap was determined mainly by radiation pressure. From the decay curve of the 2D trap, we estimated that the photon scattering rate was $\sim$100 s^{-1}. The rate determined the lifetime of the 3D trap: the trapped atoms were heated by stochastic scattering events, and those having kinetic energy exceeding the potential barrier eventually escape from the novel trap. This consideration agrees with the fact that the observed temperature of the trapped atoms is close to the estimated potential height and independent of the trapping time (Fig. 3).

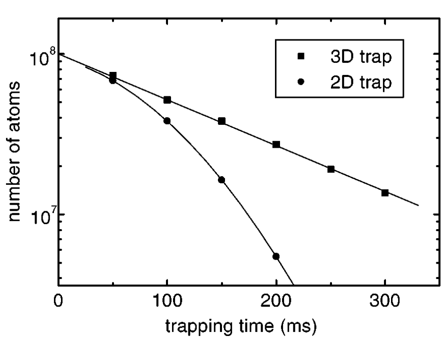

FIG. 4. Decay of atoms from the 2D (full circle) and 3D (full square) trap.

In the first stage of the present study, we used the LG_{01} beam for trapping. The lifetime, however, was only a few tens of milliseconds, which is shorter than that with the LG_{03} beam. The reason was that a lower-l doughnut beam possesses a smaller dark spot where the photon scattering rate is small. Therefore, we expect that the lifetime of the novel trap will be considerably extended by using a doughnut beam which is not only intense with large detuning but also high in l. Such a beam is efficiently produced from the Gaussian laser beam by a blazed phase hologram [14]. Experimental study is now in progress.

We have trapped laser-cooled rubidium atoms in a novel optical trap which is composed of the doughnut and plugging beams. The initial number and the temperature of the trapped atoms are about 10^8 and 18 μK. The lifetime of the trap is 150 ms, which is limited by random photon scattering. To extend the lifetime of the trap we can use the PGC, because the atoms are trapped in a dark region where the atomic energy level shift induced by the trapping beams is smaller than that induced by the PGC beam. Experimental results will appear in a separate paper.

The novel trap has great flexibility and potential for various applications: ideal circumstances are provided for precision measurements because the atoms are confined in a region of low optical field strength in absence of any external field. Besides, the 2D trap can be directly applied as a guide for atoms. Furthermore, the atomic density of the 3D trap can be increased easily just by reducing the diameter of the doughnut beam close to the diffraction limit using a system of zooming lenses. Although this compression results in adiabatic heating, a cooling mechanism such as a PGC works even in the novel optical trap and removes the heat. We expect the novel trap to increase the atomic phase space density and hopefully to realize BEC.

This work has been supported by a Grant-In-Aid from the Ministry of Education, Science, and Culture; the Sumitomo Foundation; and the Core Research for Evolutional Science and Technology (CREST) of the Japan Science and Technology Corporation. We wish to thank F. Shimizu for his loan of an Ar-ion laser.

[1] S. Chu, L. Hollberg, J.E. Bjorkholm, A. Cable, and A. Ashkin, Phys. Rev. Lett. **55**, 48 (1985).
[2] E.L. Raab, M. Prentiss, A. Cable, S. Chu, and D.E. Pritchard, Phys. Rev. Lett. **59**, 2631 (1987).
[3] P. Lett, R.N. Watts, C.I. Westbrook, W.D. Phillips, P.L. Gould, and H.J. Metcalf, Phys. Rev. Lett. **61**, 169 (1988).
[4] M. Kasevich and S. Chu, Phys. Rev. Lett. **69**, 1741 (1992); N. Davidson, H.-J. Lee, M. Kasevich, and S. Chu, Phys. Rev. Lett. **72**, 3158 (1994).
[5] A. Aspect, E. Arimondo, R. Kaiser, N. Vansteenkiste, and C. Cohen-Tannoudji, Phys. Rev. Lett. **61**, 826 (1988); J. Lawall, S. Kulin, B. Saubamea, N. Bigelow, M. Leduc, and C. Cohen-Tannoudji, Phys. Rev. Lett. **75**, 4194 (1995).
[6] M.H. Anderson, J.R. Ensher, M.R. Matthews, C.E. Wieman, and E.A. Cornell, Science **269**, 198 (1995); K.B. Davis, M.-O. Mewes, M.R. Andrews, N.J. van Druten, D.S. Durfee, D.M. Kurn, and W. Ketterle, Phys. Rev. Lett. **75**, 3969 (1995).
[7] C.S. Adams, H.J. Lee, N. Davidson, M. Kasevich, and S. Chu, Phys. Rev. Lett. **74**, 3577 (1995).
[8] N. Davidson, H.J. Lee, C.S. Adams, M. Kasevich, and S. Chu, Phys. Rev. Lett. **74**, 1311 (1995).
[9] H.J. Lee, C.S. Adams, M. Kasevich, and S. Chu, Phys. Rev. Lett. **76**, 2658 (1996).
[10] L. Allen, M.W. Beijersbergen, R.J.C. Spreeuw, and J.P. Woerdman, Phys. Rev. A **45**, 8185 (1992).
[11] M. Kristensen, M.W. Beijersbergen, and J.P. Woerdman, Opt. Commun. **104**, 229 (1994); H. He, M.E.J. Friese, N.R. Heckenberg, and H. Rubinsztein-Dunlop, Phys. Rev. Lett. **75**, 826 (1995); M.E.J. Friese, J. Enger, H. Rubinsztein-Dunlop, and N.R. Heckenberg, Phys. Rev. A **54**, 1593 (1996).
[12] W.L. Power, L. Allen, M. Babiker, and V.E. Lembessis, Phys. Rev. A **52**, 479 (1995); M. Babiker, V.E. Lembessis, W.K. Lai, and L. Allen, Opt. Commun. **123**, 523 (1996).
[13] V.Y. Bazhenov, M.S. Soskin, and V. Vasnesov, J. Mod. Opt. **39**, 985 (1990); N.R. Heckenberg, R. McDuff, C.P. Smith, H. Rubinsztein-Dunlop, M.J. Wegner, and A.G. White, Opt. Quantum Electron. **24**, S951 (1992).
[14] K.T. Gahagan and G.A. Swartzlander, Jr., Opt. Lett. **21**, 827 (1996); H. He, N.R. Heckenberg, and H. Rubinsztein-Dunlop, J. Mod. Opt. **42**, 217 (1995).
[15] W.D. Phillips, in *Fundamental Systems in Quantum Optics*, Proceedings of the Les Houches Summer School (North-Holland, Amsterdam, 1992).
[16] C. Monroe, W. Swann, H. Robinson, and C. Wieman, Phys. Rev. Lett. **65**, 1571 (1990).
[17] M.W. Beijersbergen, L. Allen, H.E.L.O. van der Veen, and J.P. Woerdman, Opt. Commun. **96**, 123 (1993).