Guiding of Atoms in a Dark-hollow Laser Beam

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It is experimentally demonstrated that trapped cold Rb atoms are guided in the atomic funnel which is made by a dark, hollow laser beam produced by coupling intense laser light into a micron-sized hollow-core optical fiber. The guided atoms will be used to enhance the atomic density inside a hollow-core optical fiber.

Atomic guiding in an atomic funnel is very useful for many interesting atom optical experiments requiring the precise control of atomic motion. So far, two kinds of atomic guiding schemes have been proposed and studied, both theoretically [1–3] and experimentally [4–6]. The authors of Ref. 1 proposed laser wave guiding of the atoms in a large, hollow optical fiber by using a Gaussian laser beam with a negative frequency detuning [1,4]. The successful realization of this proposal is reported in Ref. 2. Another is evanescent wave guiding in a small fiber by means of an evanescent wave field with blue detuning [2,3,5,6]. Atoms propagate in such a waveguide by reflection from the evanescent light wave.

Recently, Balykin et al. [7] proposed a method to guide ultracold atoms from a magneto-optical trap (MOT) by use of an evanescent wave field with blue detuning in a curved, convergent, hollow optical waveguide. Theoretical analysis shows that this method can further cool atoms and increase the phase density of atoms.

For these experiments, however, the coupling efficiency of the incident atoms into the hollow core was very low due to tight collimation of the thermal atomic beam. In order to guide the trapped cold atoms and further enhance the atomic density inside the hollow core, we have demonstrated an atomic funnel made of a diverging, dark, hollow laser beam produced by coupling intense laser light into a hollow-core optical fiber. In our scheme, we have achieved high atom-guiding efficiency by use of an elongated doughnut-shaped laser beam. Furthermore, there are several potential advantages, such as cooling effects and an atomic phase density increase [7,8].

We have obtained a doughnut-shaped laser beam by coupling a Ti:sapphire laser into a hollow-core optical fiber (5-μm hollow diameter) and collimating the output laser beam of the fiber with a microscope objective lens [9]. The size of the doughnut-shaped beam can be varied easily by adjusting both the magnification of the collimating lens and the propagation distance. In the experiment, we used a doughnut-shaped beam with a 1-mm inner diameter and a 2.8-mm outer diameter at the trapping position (about 1 m away from the objective lens).

Obviously, when the laser frequency is larger than an atomic resonance, the doughnut-shaped beam has a repulsive potential \(U(r)\) which is very similar to the one for an evanescent wave in a hollow optical fiber. For two-level atoms, the potential \(U(r)\) due to the reactive interaction of photons and atoms is given by

\[
U(r) = \frac{\hbar \Delta}{2 \log \left( 1 + \frac{I(r)/I_s}{1 + 4 \Delta^2 / \Gamma^2} \right)}
\]

where \(\Delta = \omega_L - \omega_0\) is the laser detuning from resonance, \(I_s\) is the saturation intensity, \(I(r)\) is the guiding laser intensity, and \(\Gamma\) is the spontaneous decay rate.

Figure 1 shows the experimental setup for guiding \(^{85}\)Rb atoms. We cooled and trapped about \(10^7\) \(^{85}\)Rb atoms by using an external-cavity diode laser system in a MOT [10–12]. The frequency of the trapping laser was red-detuned with respect to the \(5S_{1/2}, F = 3 \rightarrow 5P_{3/2}, F' = 4\) line, and the repumping laser, which was used to prevent...
the atoms from being accumulated in the $F = 2$ ground state, was tuned to the $5S_{1/2}, F = 2 \rightarrow 5P_{3/2}, F' = 3$ line.

The doughnut-shaped beam generated by the Ti:sapphire laser was overlapped with a vertical pair of trapping beams at the polarizing beam-splitter (PBS) cube. We used a mechanical shutter to block the upward trapping beam on the axis in order to push the MOT downward along the atomic funnel. When the upward retroreflecting beam is blocked, the trapped atoms are pushed downwards due to the radiation-pressure imbalance. If the transverse kinetic energy of an atom is smaller than the optical potential of the blue-detuned doughnut-shaped beam, the atom is reflected by that beam and guided along the beam.

We used a probe laser whose frequency was tuned to the $5S_{1/2}, F = 3 \rightarrow 5P_{3/2}, F' = 4$ resonance line to illuminate a location at a distance of 12 cm below the trap. The repumping laser was also added to the detection region to increase the detection efficiency. When the guided atoms arrived at the detection region in 16–17 ms after release, the fluorescence was measured by photomultiplier tube. Figure 2 shows typical guiding signals for different detunings of the guiding laser. We can observe the guiding effect in the 1–5 GHz blue-detuning range of the guiding laser. Without the guiding beam or with a red-detuned guiding laser, we can obtain only a small signal which is caused by the atoms that were released from the MOT.

From the experimental data (triangular symbols) in Fig. 3, we can also clearly see the largest guiding signal occurs at a blue detuning of 3 GHz. The reason for this enhancement is that there is an optical pumping effect due to the dark, hollow beam. Note that since the laser light is blue detuned to the line from the $F = 3$ state to the excited states, but red-detuned to the line from the $F = 2$ state, the atoms in the $F = 2$ state cannot be guided. When the guiding laser is blue detuned by about 3 GHz, the atoms in the $F = 2$ state are pumped to the $F = 3$ state, so most of the atoms are in the $F = 3$ state in this case. Therefore, we expect a larger guiding signal. In Fig. 3, the background guided atomic flux (normalization signal) obtained without the guiding beam is about 0.15. In Fig. 3, we also plot the theoretical values (round symbols) in which the optical pumping effect and the tunneling effect are included. We see that it is in good agreement with the experimental curve (details will be published elsewhere).

In conclusion, we have guided trapped cold Rb atoms in an atomic funnel made of a dark, hollow laser beam produced by coupling intense laser light into a micron-sized hollow-core optical fiber. The guided atoms are directly coupled into the hollow core without using a lens to enhance the atomic density inside the hollow-core re-
region. It is possible that the temperature of the atoms may be decreased as well as guided, and thus they can be used as a bright source of deBroglie waves.

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REFERENCES