Laser Spectroscopy of Atoms Guided by Evanescent Waves in Micron-Sized Hollow Optical Fibers

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We report the first laser spectroscopic experiments on the Rb beam guided by blue-detuned evanescent waves in micron-sized hollow fibers. The two-step photoionization spectra show the long-range dispersive properties of dipole interaction between guided atoms and evanescent waves. A large enhancement factor of 20 in in the transmitted atomic flux is obtained at optimal conditions and the total guidance efficiency is estimated to be above 40%. The state- and species-selective guide with proper frequency detunings of the guide laser realizes in-line spatial separation of two stable Rb isotopes. [S0031-9007(96)00434-6]

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As a feasible method to realize a precise manipulation of neutral atoms, two kinds of atomic waveguides using optical fibers have been proposed [1–4]. The first is one using a red-detuned Gaussian laser beam propagating into a hollow-core fiber [1]. The dipole force from the intense Gaussian beam guides atoms by attracting them to the center of the hollow region where the laser intensity is maximum. However, it causes strong heating of the guided atoms due to the spontaneous emission. The other scheme is one using evanescent waves such that the spontaneous-emission effect is relatively negligible [2–4]. The evanescent wave produced near a glass-vacuum interface acts as a mirror for atoms under blue detuning [5], which leads from the walls within only a few hundred nanometers for visible light. Therefore, the guided atoms interact with the light field only when they approach the walls, but otherwise they are free. The atom guidance with the evanescent wave enables one to use a hollow fiber with a small hollow diameter of 1 μm. Such a micron-sized atom guide will not only enhance the precision of atom manipulation but will also be useful for interesting studies such as the cavity QED effects in a cylindrical dielectric, the gravitational cavity [6], the atomic quantum wire [7], and the atom lithography [8].

The experimental demonstration of the Rb atom guidance were performed in hollow-core glass capillaries with relatively large hollow diameters of more than 20 μm [9,10]. They employed the hot-wire technique and detected four kinds of Rb atomic states including two isotopes at the same time so that the dependence of the guidance on the frequency detuning is ambiguous. In this Letter, we report the first laser-spectroscopy experiments on the Rb atomic beam guided by the blue-detuned evanescent wave in the cylindrical-core hollow fibers with 7- and 2-μm hollow diameters. The hollow areas are 10 and 100 times smaller than that of the glass capillary used in Ref. [10]. The combination of the small hollow fibers and the collimated atomic beam realizes the high efficient guidance and the fine control of the lateral atomic motion, which allows one to detect the cavity QED effects.

First of all, we have performed two-step photoionization spectroscopies on the guided Rb atoms with micron-sized hollow fibers. The result clearly shows the long-range dispersive characteristics of the optical dipole interaction between the guided atoms and the evanescent field. Contrary to the glass capillary scheme, since the energy of the laser field is stored in the 4-μm thin cylindrical core, even a small coupled power from a guide laser beam can produce an optical potential barrier high enough to guide a thermal atomic beam. Consequently, a large enhancement factor of 20 in the flux of the transmitted ^{85}Rb atoms is obtained for a 3-cm-long hollow fiber with a 7-μm hollow diameter. We also estimate that more than 40% of the incident atoms are guided by the fiber with 280-mW coupled power at an optimal detuning. Finally, we have performed an in-line isotope-separation experiment for the two stable Rb isotopes by the state- and species-selective guidance of atoms through the fiber under proper frequency detunings of the guide laser.

Let us first consider that a laser beam with the frequency ω and the wave number k is coupled into the cylindrical core of a hollow fiber having a propagation constant β. For atoms with resonance frequency ω_0 and longitudinal velocity v_z along the waveguide, the evanescent wave leaked into the hollow region produces an optical potential $U_{\rm op}(r,\theta)$ at a distance r from the fiber center and an azimuthal angle θ given by [5]

$$U_{\rm op}(r,\theta) = \frac{1}{2}\hbar\Delta \ln\left\{1 + \frac{P(r,\theta)/P_0}{1 + 4\Delta^2/\Gamma^2}\right\}, \qquad (1)$$

where Γ, P_0, and $\Delta = \omega - \omega_0 - \beta v_z$ are the natural linewidth (= 6.1 MHz), the saturation intensity

($= 1.6\ \mathrm{mW/cm^2}$), and the frequency detuning, respectively. As shown in previous works [4], the weakly guiding approximation can be applied to describe the hollow fiber having a small refractive-index difference between core and cladding. As a result, it greatly simplifies the description of the evanescent waves in terms of the linearly polarized (LP) modes. Under this approximation, the intensity $P(r,\theta)$ of the LP_{m1} evanescent wave can be written as [4]

$$P(r,\theta) = \frac{\beta}{2\omega\mu_0} C^2 I_m^2(\upsilon r)\cos^2(m\theta), \tag{2}$$

where $\upsilon = \sqrt{\beta^2 - k^2}$, μ_0 is the magnetic permeability, and $I_m(\upsilon r)$ is the modified Bessel function of the first kind of order m, respectively. The constant C can be determined by the boundary conditions and the laser power. Note that the total atomic potential consists of the repulsive optical barrier $U_{\mathrm{op}}(r,\theta)$ due to the evanescent wave in Eq. (1) and the attractive cavity potential $U_{\mathrm{cp}}(r)$ due to the atomic interaction with the surrounding cylindrical surface of the core [4]. Provided that the evanescent wave is sufficiently intense, the total potential becomes positive so that atoms can be reflected and guided.

Figure 1 shows a schematic diagram of the experimental setup. A thermal atomic beam from a heated Rb oven, which was collimated within 1 mrad, was introduced into the hollow fiber having a hollow diameter of 7 μm (2 μm), core thickness of 3.8 μm (4 μm), and length of 3 cm. The atoms which do not enter the hollow region upstream were blocked by a large fiber holder so that they are not detected downstream. We aligned the straight hollow fiber with the atomic beam path using a He-Ne laser. A guiding laser beam from a Ti:sapphire laser was coupled at the core at the entrance by a mirror with a hole that allowed the atoms to pass. The coupling efficiency of the guide laser into the core was about 40%. At the wavelength of 780 nm for guiding the Rb atoms,

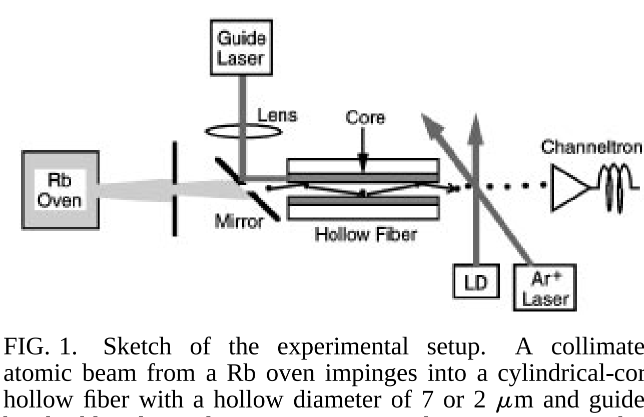

FIG. 1. Sketch of the experimental setup. A collimated atomic beam from a Rb oven impinges into a cylindrical-core hollow fiber with a hollow diameter of 7 or 2 μm and guided by the blue-detuned evanescent waves therein. A Ti:sapphire laser, focused on the core in the upstream, is used for atom guidance and isotope separation. A diode laser and an Ar-ion laser, overlapping downstream, are used for the two-step photoionization spectroscopy.

three propagation modes can be excited: LP_{01}, LP_{11}, and LP_{21} [4]. The mode patterns at the exit facet of the fiber were monitored by a charge coupled device camera from the outside of the ultrahigh vacuum chamber. In the 3-cm-long fiber, although the three modes were not clearly distinguished, an effectively round mode (i.e., $m = 0$) could be excited.

For the spectroscopy on the Rb atoms guided through the hollow fibers, we employed the two-step photoionization (PI) technique using two overlapping lasers near the exit of the fiber downstream. The ions, produced by the ionized atoms, were then detected by a channel electron multiplier (CEM) biased at a high voltage of -3 kV. A grating-feedback diode laser tuned to a wavelength of 780 nm saturates the $5S_{1/2} \rightarrow 5P_{3/2}$ transition. At the same time, an Ar-ion laser focused on the 100-μm beam waist ionizes the atoms in the $5P_{3/2}$ state (the ionization level is at 4.177 eV above the ground state). With the applied high bias, the photoionization at three wavelengths of 457.9, 476.5, and 488 nm from the Ar-ion laser was possible. The ionization efficiency of this scheme can be estimated by using the ionization cross section of the $5P_{3/2}$ state ($\sigma_i \approx 10^{-17}\ \mathrm{cm}^2$) [11] and the condition of efficient ionization [12]

$$P_i \approx P_0(\sigma_0/\sigma_i), \tag{3}$$

where P_i and σ_0 are the optimum ionization-laser intensity and the resonant excitation cross section for the $5S_{1/2} \rightarrow 5P_{3/2}$ transition, respectively. Therefore, with an Ar-ion laser with 4 W focused on a spot of 100-μm diameter, we estimate the PI efficiency to be 32%. Assuming the quantum efficiency of the CEM to be 0.9, the total detection efficiency is then 29%.

An enhanced transmission of the guided atoms is expected at the blue detuning of the guide laser. Figure 2 shows a Doppler-free photoionization signal for the ^{85}Rb atoms in the $F = 3$ hyperfine level of the ground state passed through the 7-μm hollow fiber as a function of the frequency detuning of the guide laser with a coupled power of 130 mW. Note that the detuning is measured with respect to the transition frequency of the upper $F = 3$ level and does not include the Doppler shift $\beta\upsilon_z$. The oven temperature of 160 °C provides a most probable longitudinal velocity of 292 m/s and a most probable transverse velocity of 0.3 m/s for our collimation angle. The incident flux of the Rb atoms impinging on the hollow entrance of 7-μm diameter is estimated to be $10^6\ \mathrm{s}^{-1}$[13] (note that the ^{85}Rb isotope occupies 73% of the incident atoms). The diode laser was tuned to the $5S_{1/2}, F = 3 \rightarrow 5P_{3/2}, F = 4$ transition and the Ar-ion laser was wavelength selected at 476.5 nm with a power of 4 W to ionize the guided atoms. In Fig. 2, we observe the expected dispersive spectrum with a peak at a blue detuning of 2.7 GHz. The foot level of the ion-counting signal extended over a 20-GHz detuning. The maximum atom flux at the transmission peak was $3 \times 10^4\ \mathrm{s}^{-1}$ as

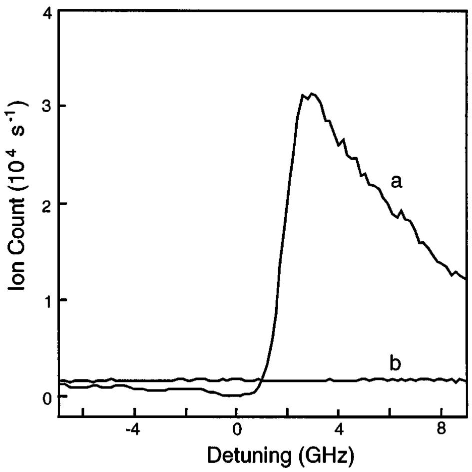

FIG. 2. Ion-counting rates for the transmitted atoms versus the frequency detunings of the guide laser in the 7-μm hollow fiber. The guide laser with 130 mW power is on in (a) and off in (b). The detuning is measured with respect to the resonance frequency of the $5S_{1/2}, F = 3 \rightarrow 5P_{3/2}, F = 4$ transition of ^{85}Rb. The grating-feedback diode laser is locked to this D_2 line and the Ar-ion laser is selected at a wavelength of 476.5 nm with 4 W power.

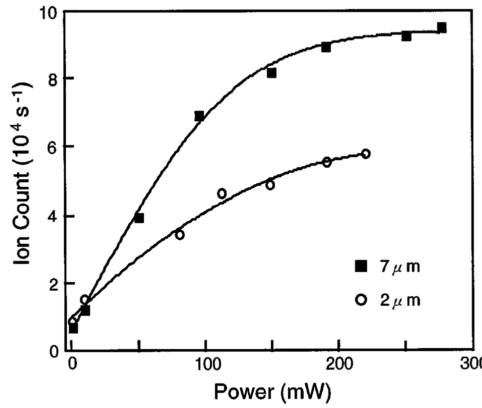

FIG. 3. Variation of the guided atomic flux versus the coupled power of the guide laser in the 7- and 2-μm hollow fibers. The background level in the absence of the guide laser is subtracted from the observed lux of ^{85}Rb in the $F = 3$ level. We estimate that the total guidance efficiency is more than 40% in the case of the 7-μm hollow fiber.

shown in Fig. 2(a). On the other hand, flux without the guide laser was 1.5×10^3 s^{-1} as shown in Fig. 2(b). Therefore, we estimate a very large enhancement factor of 20, which is possible due to the use of the well-collimated atomic beam and the micron-sized hollow fiber.

In the red-detuning region, however, the atomic flux was decreased below the background level without the guide laser probably due to adsorption on the inner wall by the attractive optical force. Moreover, in the vicinity of the $5S_{1/2}, F = 3 \rightarrow 5P_{3/2}, F = 4$ resonant transition, it seems that the ^{85}Rb atoms in the $F = 3$ ground-state hyperfine level are pumped into the lower $F = 2$ level due to the interaction with the resonant evanescent wave of the guide laser which is slightly leaked into the hollow region at the entrance. We have confirmed this effect by detecting the guided atoms in the lower hyperfine level by tuning the diode laser to the $5S_{1/2}, F = 2 \rightarrow 5P_{3/2}, F = 1$ transition. As a result, a small increase (about 30% of the background signal) of the ^{85}Rb atoms in the $F = 2$ level was observed near the resonant guidance frequency of the $5S_{1/2}, F = 3 \rightarrow 5P_{3/2}, F = 4$ transition.

Figure 3 shows the transmitted ^{85}Rb atom flux in the $F = 3$ level as a function of the coupled power of the guide laser at the optimal detuning of 2.7 GHz. The oven temperatures were 174 and 183 °C in the case of the 7- and 2-μm hollow fibers, respectively. The flux is plotted after the background signal without the guide laser is subtracted (1.6×10^4 s^{-1} for the 7-μm hollow fiber). Therefore, the data in Fig. 3 represent the net transmission flux only due to the optical guidance. As shown in the curve for the 7-μm hollow fiber, saturation behavior in the transmission can be observed as the coupled power is increased above 150 mW or so. Moreover, a maximum net flux of 9.5×10^4 s^{-1} could be obtained at the 280 mW power. Using the total detection efficiency of 29% and the incidence flux of 9×10^5 s^{-1} for the ^{85}Rb isotope, and also adding the background signal, we estimate that the total guidance efficiency of the atom waveguide is about 43% for the ^{85}Rb atom in the $F = 3$ level, whereas the pure optical guidance efficiency is 37%.

If we take into account the fact that the ^{87}Rb isotope [see Fig. 4(a)] as well as the ^{85}Rb atoms in the lower $F = 2$ level are also guided, we estimate the total efficiency exceeds 50%. The very high guidance efficiency is realized mainly because we have used a collimated atomic beam, which is discussed in the following. In the case of the excitation of the LP_{01} mode at a 300 mW power and a 3 GHz blue detuning in the 7-μm hollow fiber, from Eqs. (1) and (2), we obtain the optical potential of 120 mK in terms of the equivalent temperature of the atomic kinetic energy, which then corresponds to the maximum transverse velocity of 3.4 m/s that can be reflected. Therefore, since the most probable transverse velocity due to our beam collimation is 0.3 m/s, most of the atoms entering the hollow fiber are expected to be guided.

Now, let us consider the cavity potential $U_{\mathrm{cp}}(r)$ which reduces the height of the optical potential barrier. By using the results of the two parallel-dielectric case [14,15], we can roughly estimate the effects of the cavity potential [5]. For the excitation of the LP_{01} mode at 280 mW in the 7-μm hollow fiber, a reduction of about 30% occurs in the potential barrier. On the other hand, with 1 mW power, the potential barrier almost disappears due to the attractive cavity potential. The ^{85}Rb atoms can be guided above the coupled power of 1 mW as shown in Fig. 3, but we observe a rapid decrease of the guided flux below 1 mW.

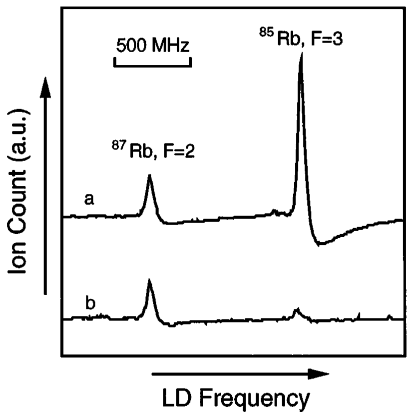

FIG. 4. In-line separation of the two stable Rb isotopes. Atomic transmission signals as a function of the diode-laser frequency are presented at a large blue detuning for both Rb isotopes in their upper hyperfine levels (a), and at a blue detuning for ^{87}Rb but near red detuning for ^{85}Rb (b).

Note that the maximum transverse velocity due to $U_{\mathrm{op}}(r)$ for 1 mW power is about 0.3 m/s, which is equivalent to that determined by the beam collimation. Therefore, the observed threshold behavior near 1 mW power may be considered as an indirect indication of the cavity QED effects of the cylindrical dielectric. In order to study the cavity QED effects more quantitatively, we measured a guide-laser power that does not increase the transmission on ^{87}Rb atoms in the upper ground state with the 2 μm hollow fiber. The result shows a threshold power of 2 mW, which agrees well with the theoretical calculation. The detailed results will be published elsewhere.

Finally, we have performed an isotope-separation experiment for the two stable Rb isotopes in their upper hyperfine levels of the ground state, by the state-selective and species-selective guidance of atoms in the fiber which is done with proper frequency detunings of the guide laser. Based on the dispersive nature of the guidance shown in Fig. 2, we can select a specific isotope by adjusting the guide-laser frequency. Figure 4 shows a demonstration of the isotope separation by the 7-μm hollow fiber. The upper hyperfine levels of the ground states of the two isotopes ^{85}Rb and ^{87}Rb are separated by about 1 GHz. In Fig. 4(a), the laser frequency was set at a large blue detuning for both the $5S_{1/2}, F = 2$ level of ^{87}Rb and the $5S_{1/2}, F = 3$ level of ^{85}Rb. On the other hand, in Fig. 4(b), the laser was blue detuned for the ^{87}Rb atoms but nearly red detuned for the ^{85}Rb atoms. As is clear in the figure, the transmission flux of the ^{85}Rb isotope is greatly suppressed down to one-tenth of the background level. Therefore, our hollow fiber can be considered as an in-line isotope separator or an atomic-state filter.

In conclusion, the two-step photoionization spectroscopy has been performed so that the long-range dispersive character of the atom-field interaction has been clearly observed. The precise control of the atomic lateral motion has been realized within 2 μm through a long distance. We have shown that more than 40% of the incident atoms are guided, and obtained a large guiding enhancement factor of 20; they are 40 and 7 times improvement over the result in Ref. [10], respectively. Moreover, the state selectivity and species selectivity have been demonstrated through a separation between two Rb isotopes. Since the evanescent wave is localized within the size of an object [16], we may even manipulate atoms with a nanometric accuracy using a sharpened tip on an optical fiber [17]. The atom guidance in very small hollow fibers will open a new way to such a nanoscale atom manipulation as well as novel atomic physics experiments.

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