High-Density Trapping of Cold Ytterbium Atoms by an Optical Dipole Force

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We have succeeded in trapping a high density of rare-earth atom of ytterbium (Yb) in a crossed far-off resonance trap. The peak density reaches more than 10^{14} cm^{-3}. With a new method of a delayed crossed far-off resonance trap, we have elucidated that the atoms became concentrated into the cross region by atom-atom collisions. We trap fermionic Yb atoms in the same way as bosonic ones.

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An optical far-off resonance trap (FORT) [1] has been widely used because of its good controllability, strong confinement, and ability to trap all spin states. In almost all FORT experiments, the FORT beams were irradiated into atom clouds in optical molasses or a magneto-optical trap (MOT) in order to load atoms into the FORT. During loading, the light used for optical molasses or MOT induced light-assisted collisions and thus typically limited the atom density to about 10^{12} cm^{-3} [1–3]. Although some groups succeeded in higher density trapping by additional cooling or a compression in the FORT, the obtained density was less than 10^{14} cm^{-3} [4,5]. Recently, extremely high-density trapping of ^{87}Rb atoms and ^{6}Li atoms of more than 10^{14} cm^{-3} and, in consequence, the realization of all-optical Bose-Einstein condensation (BEC) [6] and Fermi degeneracy [7] were reported. It has not been clear why such high atom density trapping was realized, and the interesting physics behind these observations remains to be revealed.

In this Letter, we report on the creation of an extremely high atom density in a FORT of ytterbium (Yb) atoms. The density reached more than 10^{14} cm^{-3} in a crossed FORT. By developing a new scheme of crossed FORT, we have discovered that atom-atom elastic collisions in the trap played a vital role in the realization of the extremely dense atomic sample in the crossed FORT. It is also noted that the dense and cold fermionic gases of ^{171}Yb and ^{173}Yb could be produced in exactly the same experimental configuration as the bosonic gases of ^{172}Yb, ^{174}Yb, and ^{176}Yb.

These results suggest that the FORT using Yb atoms is a quite promising system for optical creation of quantum degenerate gases, which is greatly encouraged by the quite recent success of all-optical formation of ^{87}Rb BEC [6] and ^{6}Li Fermi degeneracy [7]. The Yb BEC would provide a purely scalar wave atom laser, unperturbed by a magnetic field, in contrast to the alkali atom BEC, which is interesting in atom optics. Yb is also attractive to optically realize bosonic-bosonic, bosonic-fermionic, fermionic-fermionic quantum degenerate gases, owing to its rich isotopes (five bosons and two fermions). It is also noted that the optically trapped Yb atoms have other important applications, especially in fundamental physics such as the test of time-reversal symmetry [8] and parity violation [9].

The Yb atom is rare earth but has an alkaline-earth-like electronic structure, and thus has two cooling transitions: a dipole-allowed ($^1S_0$-$^1P_1$) transition whose wavelength is 399 nm and an intercombination ($^1S_0$-$^3P_1$) transition whose wavelength is 556 nm. We initially Zeeman-slowed the atoms with the dipole-allowed transition. Then we cooled atoms to a temperature below the potential depth of the FORT with a MOT using the intercombination transition, which was described in detail in Refs. [10,11]. Typically there were 10^7 atoms in the MOT, and the peak density was about 10^{12} cm^{-3}. The temperature of atoms was about 40 μK.

To trap many atoms in a small region at a high density, we adopted red-detuned crossed beam configuration formed by crossing two focused beams at a right angle at their foci [5,12]. The FORT beams were generated with a cw green diode-pumped solid-state laser whose wavelength was 532 nm, and output power was 10 W. In order to control the FORT laser intensity electronically, we used the first-order diffracted beam from an acousto-optic modulator (AOM) as the FORT beams. We adopted two kinds of setups in the experiments. In setup I, we used the beam that passed through the atoms for the second FORT, which is shown in Fig. 1. The two beams were crossed in the horizontal plane. The other setup consists of two beams split from the same laser by a polarizing beam splitter, and the laser intensities could be independently controlled by the respective AOMs. One of the two FORT beams is horizontal, and the other is vertical. This setup is referred to as setup II below.

Our FORT experiments were carried out as follows. After about 4 s loading of the Yb atoms from the atomic beam into the MOT using the intercombination transition, we irradiated the atom cloud with the two beams for the crossed FORT. During the period in which both the MOT and the FORT beams were turned on, a fraction of atoms were successfully transferred into the crossed FORT. The MOT beams were turned off 50 ms after turning on the FORT beams. From this moment ($t = 0$) when the MOT beams were turned off, the atoms started to be trapped in the crossed FORT alone. Finally, the atoms in the crossed

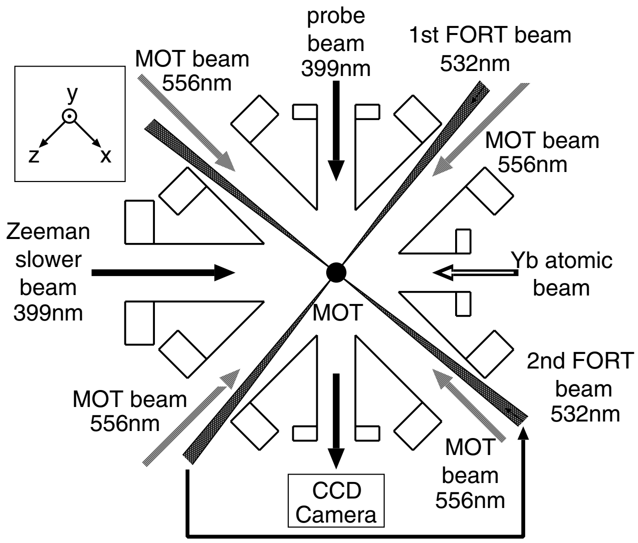

FIG. 1. Top view of the typical experimental setup of a crossed FORT which consists of two right-angled beams. Two counterpropagating MOT beams perpendicular to this paper are omitted in this figure. This setup is referred to as setup I in the text.

FORT were observed with an absorption image method using the dipole-allowed transition (399 nm).

Figure 2(a) shows a typical absorption image signal in setup I, in which the ^{174}Yb atoms trapped in the crossed FORT are clearly observed. The image shown in Fig. 2(a) was taken 10 ms after turning off the MOT beams. It is noted that the propagation axis of the probe beam lay in the plane of the two FORT beams (z-x plane in Fig. 1), and thus the atoms trapped in the two beams were almost overlapped in the images [13]. The maximum number of the most abundant isotope ^{174}Yb atoms in the FORT was about 3×10^6, which corresponded to 15% of the atoms initially trapped in the MOT. It is interesting to note that this maximum atom number in the FORT did not so sensitively depend on the initial atom number in the MOT. This behavior suggests that the loading into the FORT is limited by light-assisted collisions at a high atom density as in the previous experiments [3]. Out of the trapped atoms, 2×10^5 atoms were concentrated in the crossed region [see Fig. 2(b)]. We defined the cross region and obtained the number of the atoms in the cross region N_c by the following procedure. Absorption images give us the column atom density $n(X, Y) = \int dZ n(X, Y, Z)$, where Z is the propagation direction of the probe laser. We first calculated the line atom density $n(X)$ along the horizontal direction X by integrating the column atom density $n(X, Y)$ along the vertical direction Y. Second, we fitted the obtained line atom density near the cross region to the function $n(X) = a_1 \exp[-(X/X_0)^2] + a_2$, where fitting parameters are a_1, X_0, and a_2. Figure 2(b) shows the typical quality of the fits. As is known from Fig. 2(b), the fittings are usually good enough. The first term $n_c(X) = a_1 \exp[-X/(X_0)^2]$ corresponds to the atoms in the cross region, which is superposed on the signals of atoms in the single FORT beam a_2. By integrating only the $n_c(X)$, we obtained the number of the atoms in the cross region N_c, which is expressed as $\sqrt{\pi} a_1 X_0$. The temperature of the atoms in the FORT was measured to be about 100 μK by the time-of-flight method. A similar value was obtained in the single beam FORT. The maximum atom number in setup II was 1×10^6, and out of the trapped atoms, 1×10^5 atoms were in the cross region. The temperature was almost the same as that in setup I. The lifetime of the trapped atoms was about 400 ms. In setup II, we observed that the phase space density increased until 250 ms, and then decreased. This showed that atoms decayed mainly due to plain evaporation during the first 250 ms, and then decayed due to the background gas collisions at the vacuum level of 10^{-9} Torr.

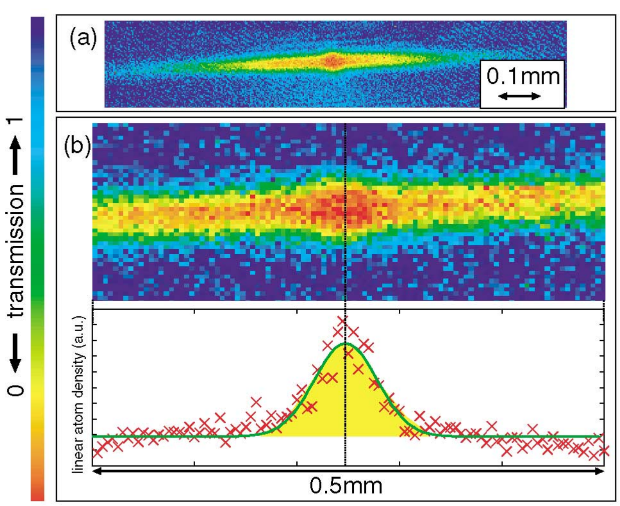

FIG. 2 (color). (a) Typical absorption image signal of the ^{174}Yb atoms trapped in the crossed FORT. (b) Enlarged signal of (a) near the cross region and the column density profile which was directly obtained from the absorption images. The green line showed the fitting line with the function $a_1 + a_2 \exp[-(x^2/x_0^2)]$. The atom number in the cross region (yellow region) was referred to as the N_c in the text.

Changing the frequencies of the MOT and the Zeeman slower beams, we could trap the bosonic isotopes of ^{172}Yb, ^{174}Yb, and ^{176}Yb, and fermionic ones of ^{171}Yb and ^{173}Yb in exactly the same experimental configuration of the crossed FORT [14]. Since the detunings ($\sim 10^{14}$ Hz) of the FORT beam from the atomic resonance frequencies were much larger than the isotope shifts ($< 10^{10}$ Hz), the FORT was expected to work equally well for all isotopes. In fact, we observed that the maximum atom number and the temperature in the FORT were almost the same except ^{173}Yb [15].

Great care was taken in the estimation of the peak atom density. Insufficient spatial resolution of about 6 μm for our image system makes a large error in straightforward estimation of the peak density from the absorption rate. Instead, we estimated the peak density n_0 from the expression of the Maxwell-Boltzmann distribution in the harmonic trap [16] $n_0 = N \times (m\bar{\omega}^2/2\pi k_B T)^{3/2}$, where N is the atom number, m is the mass of the Yb atom, ω_x, ω_y, ω_z are the trap oscillation frequencies in the respective dimension, $\bar{\omega} = (\omega_x\omega_y\omega_z)^{1/3}$ is its mean, k_B is the Boltzmann constant, and T is the temperature of atoms. The oscillation frequencies of the FORT were directly measured in setup II with the parametric resonance method where the loss of the trapped atom number was observed by modulating the FORT beam intensity [17] at the modulation frequency $\Omega_i = 2\omega_i/n$ $(i = x, y, z; n = 1, 2, \ldots)$. In the crossed FORT, three fundamental parametric resonance spectra ($n = 1$) corresponded to ω_{r1}, ω_{r2}, and $\omega' = \sqrt{\omega_{r1}^2 + \omega_{r2}^2}$, where ω_{r1} (ω_{r2}) is the radial oscillation frequency of the first (second) FORT and ω' is the combined oscillation frequency, were expected to be observed. By the careful alignment, we observed these fundamental parametric resonance at $\omega_{r1} = 2\pi \times 3.3$ kHz, $\omega_{r2} = 2\pi \times 5.0$ kHz, and $\omega' = 2\pi \times 6.0$ kHz [18]. From these oscillation frequencies ω_{1r} and ω_{2r}, the waists of the FORT beams were estimated to be 14 and 11 μm, respectively. The observed combined trap frequency ω' was consistent with the above theoretical expression of ω' in terms of ω_{r1} and ω_{r2}, and this ensured that the two FORT beams were well aligned and that it is possible to estimate the peak density using the expression above with no assumptions on the possible beam misalignment. The potential depths were estimated to be 0.43 and 0.63 mK, respectively. Because the atom temperature of 100 μK was much lower than the trap depth, there were almost no atoms in the anharmonic region, which assures the use of the expressions of the peak density n_0 mentioned above. The peak atom density in the crossed FORT n_0 was estimated to be 4.7×10^{14} cm^{-3} with the measured values of $T = 100$ μK and $N = 1 \times 10^5$, and the corresponding phase space density reached more than 10^{-3} [19].

It is noted that the obtained atom density is 1 order of magnitude larger than those obtained in other previous works [5,12] and is comparable with that obtained for ^{87}Rb in the crossed CO_2 trap [6], and even exceeds the usual limit imposed by light-assisted inelastic two-body collisions. It is, therefore, key to clarify whether such high atom density was already created in the presence of the MOT beams or later created after turning off the MOT beams. For this purpose we observed the time evolution of concentration of the atoms into the cross region after turning off the MOT. To analyze it quantitatively from the observed absorption images, we introduce the concentration ratio R defined as N_c/N_t, where N_c is the atom number in the cross region and N_t is the total atom number in the FORT [see also Fig. 2(b)].

By the measurements of the ratio R as a function of the trapping time in the crossed FORT, we discovered that the atoms became gradually concentrated into the cross region after turning off the MOT beams at $t = 0$. We also discovered that this ratio varied depending on the isotopes. Especially, among the isotopes of ^{171}Yb, ^{172}Yb, ^{174}Yb, and ^{176}Yb, for which we could trap enough atoms to measure the ratio R, we repeatedly confirmed that the ratio R for the fermion ^{171}Yb was much smaller than those for the bosonic isotopes.

The above observation strongly suggests that the high atom density was created after turning off the MOT beams through elastic atom-atom collisions. It was still unclear, however, whether there was a certain amount of concentration already at $t = 0$ or the concentration of the atoms was purely ascribed to the atom-atom elastic collision, because the atoms trapped by the FORT and those remaining in the MOT overlapped spatially for a short time after $t = 0$.

To study the collisional loading, we experimented with the delayed crossed FORT. By turning off the second FORT beam, the atoms were first loaded into the single FORT which consisted of the first FORT beam alone. After 30 ms single FORT time, atoms untrapped by the FORT were well separated spatially from the trapped atoms due to free fall by gravity. At this moment, $t' = 0$, the second FORT beam was irradiated to form the crossed FORT [20], and thus we could observe the concentration dynamics without the disturbance by untrapped atoms. It is obvious that there is no concentration of the atoms at the cross region immediately after turning on the second FORT beam. The measurements of the temporal evolution of the concentration ratio R after turning on the second FORT beam were shown in Fig. 3. We confirmed that the atom concentration into the cross region is entirely due to the effect of the atom-atom collisions.

In order to study the effect of adiabaticity of the switching time of the second FORT beam on the concentration dynamics, we carried out another experiment in setup II, in which the second FORT beam could be switched on at arbitrary time constant t_c by the use of

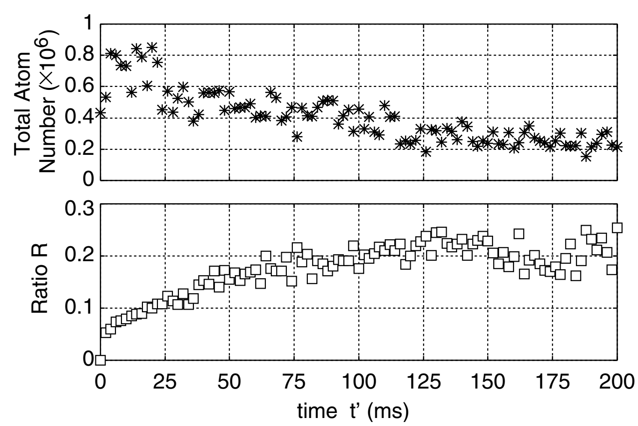

FIG. 3. Time evolution of the total atom number N_t (asterisks) and the ratio R (open squares) after a time t' from suddenly turning on the second FORT at $t' = 0$ (sudden deformation).

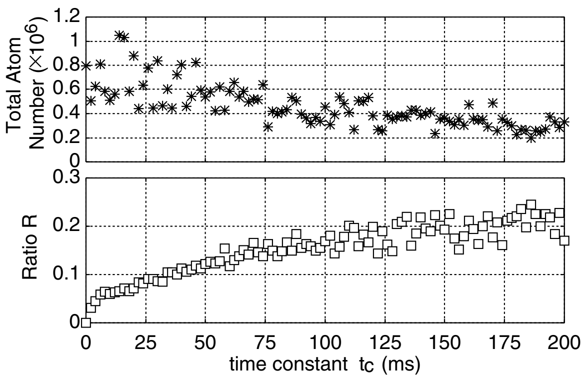

FIG. 4. Time evolution of the total atom number N_t (asterisks) and the ratio R (open squares) after gradually turning on the second FORT with a rise-up time t_c (slow deformation).

the AOM. The data shown in Fig. 4 are N_t and R as a function of the ramp-on time constant of the second FORT beam. We could not find the obvious difference between the behaviors of slow and sudden switching of the second FORT beam. The cases of slow ramping have close similarity with the previously observed phenomenon for a Bose condensate, that is, the increase of the phase space density by adiabatic deformation of the trap potential, in which atoms can be compressed by producing adiabatically a small and steep potential in a large and shallow trap [21]. The adiabatic deformation process works only for a small fraction of the atoms as explained by Stamper-Kurn *et al.* [21] in the "two-box model," which is exactly the case with the present work since R was less than 0.2 as shown in Fig. 4. From Figs. 3 and 4, the total atom number was almost constant up to 50 ms, and thus we believe that there was little effect of evaporative cooling on that time scale. The concentration ratio R of the fermion ^{171}Yb was found again to be much smaller than that of bosonic isotopes in this delayed crossed FORT for both slow and sudden switching of the second FORT beam. The time constant of building-up was about the same as those for the bosons.

Finally, we note that the high-density collisional loading demonstrated in the present paper should also work in a variety of systems. In fact, quite recently Hammes *et al.* reported a density increase after Cs atoms were loaded from a reservoir optical surface trap into a microtrap, and they concluded that this density increase was induced by elastic collisions [22]. We also believe the presented mechanism is responsible for the high ^{87}Rb atom density in the crossed FORT experiment by Barrett *et al.* [6].

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