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Optical dipole force trapping of a fermion-boson mixture of ytterbium isotopes

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We have succeeded in simultaneously trapping a fermion and boson isotope pair of ytterbium (Yb) in a far off-resonant trap (FORT). We have found evidence of elastic cross collisions between fermions and bosons, and performed a successful sympathetic cooling of the fermions. We could also enhance the loading of the fermions ^{171}Yb in the crossing region in a crossed FORT via cross collisions between the fermions ^{171}Yb and the bosons ^{174}Yb.

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Researches of highly degenerate atomic Fermi gas have been of crucial attention since the attainment of quantum degeneracy in potassium atoms [1]. Among many examples of quantum degenerate fermionic systems in nature, a dilute atomic Fermi gas is especially attractive because of its large controllability provided by easy optical manipulation. Predicted novel phenomena include the suppression of inelastic collisions [2], line narrowing through suppression of spontaneous emission [3], and the Bardeen-Cooper-Schrieffer phase transition to a superfluid state at sufficiently low temperatures [4].

To achieve quantum degeneracy of a dilute gas of bosonic atoms, i.e., atomic Bose-Einstein condensation, evaporative cooling [5] has been the key way. Thermalization of trapped atoms through atom-atom elastic collisions is very important in this method [6]. In the case of a Fermi gas, however, thermalization is suppressed in an ultralow temperature regime. For this reason, sympathetic cooling [7] has been used to cool Fermi gas of two components in some experiments [1,8]. Another interesting way is sympathetic cooling of fermions via elastic collisions between fermions and bosons [9]. It is important to trap atoms in a conservative trap such as a magnetic trap or a far off-resonant trap (FORT) [10] for efficient sympathetic cooling. Quite recently, a remarkable achievement was reported on creation of Fermi degeneracy by sympathetic cooling of magnetically trapped fermions ^{6}Li through collisions with evaporatively cooled bosons ^{7}Li [11]. This achievement is truly encouraging for performing various experiments on quantum degenerate fermion-boson mixtures using other important atomic systems.

For this purpose, rare-earth atoms of ytterbium (Yb) have some unique advantages.

(1) Low temperature can be attained using only a magneto-optical trap (MOT) utilizing the weak $^1S_0 \leftrightarrow {}^3P_1$ intercombination transition [12]. This is also the case for ^{88}Sr and ^{40}Ca which have similar energy structures, and the cooling near the photon-recoil limit has been recently demonstrated [13]. The Doppler-limit temperature is as low as 4.4 μK for Yb.

(2) An extremely high density can be obtained in a crossed FORT, which reaches $\sim 10^{14}/\mathrm{cm}^3$ [14]. It should be noted that extremely high density trapping of Rb atoms of $2\times10^{14}/\mathrm{cm}^3$ has successfully led to the all optical formation of a BEC [15].

(3) There exist rich varieties of isotopes: five bosons and two fermions. Because the natural abundances of three bosons (^{172}Yb,^{174}Yb,^{176}Yb) and two fermions (^{171}Yb,^{173}Yb) exceed 10% [16], one can easily choose fermions or bosons, as well as various combinations of mixed isotopes, that is, fermion-boson, boson-boson, and fermion-fermion. This advantage was demonstrated in a recent experiment of simultaneous multi-isotope trapping of Yb [17]. However, due to the relatively high temperature and low density associated with the MOT using the singlet transition ($^1S_0 \leftrightarrow {}^1P_1$) [18,17], it was not possible to detect interesting phenomena based on the cross collision between isotopes.

In this Rapid Communication, we report realization of optical trapping of a high-density mixture of fermion-boson isotopes (^{171}Yb-^{174}Yb). The realized low atom temperatures of 100 μK and high densities of about $10^{14}/\mathrm{cm}^3$ have enabled us to present an example of cold elastic cross collisions between fermions and bosons in an optical trap. We could perform successful sympathetic cooling of ^{171}Yb fermions via collisions between fermions and bosons in a crossed FORT. We could also enhance the loading of the fermion ^{171}Yb in the steep potential in the crossed FORT via cross collisions between the fermions ^{171}Yb and the bosons ^{174}Yb.

The experimental setup is schematically shown in Fig. 1. First, we trapped Yb isotope pairs in the MOT with the $^1S_0 \leftrightarrow {}^3P_1$ intercombination transition (556 nm) after the Zeeman slower with the dipole-allowed $^1S_0 \leftrightarrow {}^1P_1$ transition (399 nm) [12]. The 399-nm laser beam for the Zeeman slower was generated by resonant frequency doubling of a cw ring Ti:sapphire laser operated at the wavelength of 798 nm. The power of about 100 mW of 399-nm light was obtained with the Ti:sapphire laser of 1 W power. The 556-nm beams for the MOT were generated by a cw ring dye laser with R110 dye, the power of which was typically about 400 mW. The dye laser frequency was narrowed to less than 100 kHz with an intracavity electro-optic modulator (EOM) and an acousto-optic modulator (AOM) outside the cavity. This narrowing was important since the line width of the $^1S_0 \leftrightarrow {}^3P_1$ transition is as narrow as 182 kHz.

For simultaneous trapping of two isotopes in the MOT, bichromatic MOT beams are required, with each frequency near resonant to the corresponding isotope. For this purpose,

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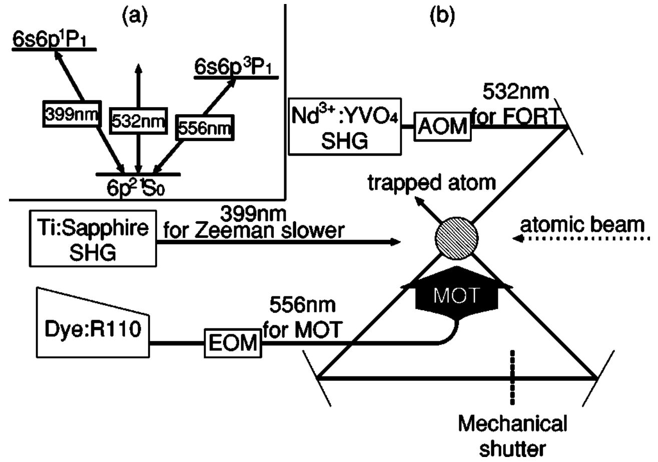

FIG. 1. (a) Energy-level diagram of Yb atom. Note that the wavelength of FORT beam is also indicated, which is red detuned from the singlet transition ($^1S_0 \leftrightarrow {}^1P_1$). (b) Schematic view of the experimental setup of a simultaneous trapping in an optical dipole force trapping. We trapped Yb atoms in the MOT using a 556-nm laser beam after the Zeeman slower with a 399-nm laser beam.

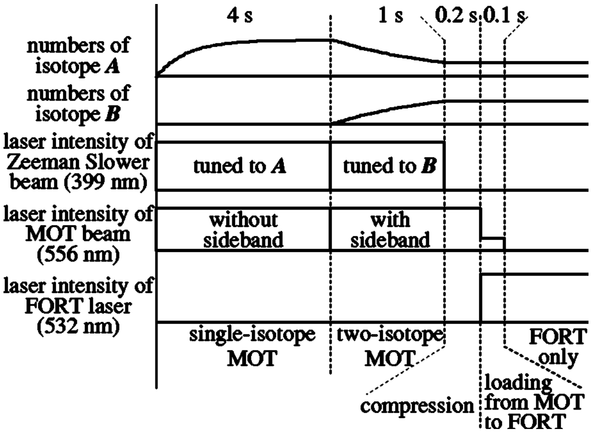

FIG. 2. Time sequence for trapping two isotopes. After loading isotope *A* into the MOT, the frequency of the 399-nm laser beam was changed so as to decelerate the isotope *B* and at the same time the sidebands on the 556-nm laser beam were generated. Thus isotope *B* was trapped in the MOT with the sideband whereas the isotope *A* remained trapped by the carrier. Then, the isotope pair was transferred into the FORT.

TABLE I. Isotope shifts from resonance frequencies of ^{174}Yb atom.

	^{171}Yb ($F=3/2$)	^{172}Yb	^{176}Yb
$^1S_0 \leftrightarrow {}^1P_1$(399 nm)	843.3 MHz	499.4 MHz	-509.4 MHz
$^1S_0 \leftrightarrow {}^3P_1$(556 nm)	3804 MHz	999.5 MHz	-953 MHz

we generated sidebands on the 556-nm light by frequency modulation with an EOM at the frequency corresponding to the isotope shift. For the 399-nm light beam for Zeeman slowing, however, no EOM can be available due to the large photorefractive effect [19] at this wavelength. Hence we designed the scheme where each isotope was loaded into the MOT during a different period. Figure 2 shows a time sequence for the simultaneous MOT of two isotopes, *A* and *B*. At first, isotope *A* was decelerated with the 399-nm laser beam and trapped in a MOT using 556-nm laser beam. After loading isotope *A* into the MOT, the frequency of the 399-nm laser beam was changed so as to decelerate the isotope *B* and at the same time the sidebands on the 556-nm laser beam were generated. Thus isotope *B* was trapped in the MOT with a sideband whereas isotope *A* remained trapped by the carrier.

As a fermion-boson mixture, we chose ^{171}Yb and ^{174}Yb. The ^{171}Yb atoms were decelerated with the $^1S_0(F=1/2) \leftrightarrow {}^1P_1(F=3/2)$ transition and trapped with the $^1S_0(F=1/2) \leftrightarrow {}^3P_1(F=3/2)$ transition. The isotope shifts of these transitions for ^{171}Yb and ^{174}Yb are listed in Table I. As the boson-boson mixture, we used ^{172}Yb-^{174}Yb and ^{176}Yb-^{174}Yb pairs. Isotope shifts in these cases are also shown in Table I.

Using this setup, we obtained a simultaneous MOT of the above-mentioned three isotope pairs. The trapped atom clouds of the two isotopes were separately observed in absorption imaging using the grating-stabilized 399-nm laser diode of about 3 mW output. The atom numbers were estimated to be 2×10^6 (^{171}Yb) and 4×10^6 (^{174}Yb) for the ^{171}Yb-^{174}Yb mixture. The temperature was $40\sim60$ μK for both isotopes. In the case of boson-boson mixtures, each atom number was about 10^6.

The FORT beam was produced by a focused 532-nm beam from a frequency doubled Nd^{3+}:YVO$_4$ laser. Since the isotope shifts ($<10^{10}$ Hz) were much smaller than the detuning of the FORT laser ($\sim10^{14}$ Hz), the FORT works equally well for different isotopes. The peak potential depth of this FORT was 810 μK, the radial oscillation frequency in the potential was 4.7 kHz$\times 2\pi$, and the axial oscillation frequency was 34 Hz$\times 2\pi$ with a beam waist of 14 μm and a power of 6.4 W [14]. To realize tight confinement in all directions, we adopted the "crossed FORT" scheme [20,21], in which two FORT laser beams were crossed at an almost right angle at their foci. To make efficient use of the available FORT beam power, we used the first FORT beam after transmission through the atoms as the second FORT beam. The peak potential depth of the second FORT was 280 μK and the axial oscillation frequency was 2.9 kHz$\times 2\pi$ with a beam power of 4.9 W and a beam waist of 16 μm. Thus the peak potential depth of the crossed FORT was 1090 μK.

Transferring atoms from the MOT into this FORT, we could optically trap a fermion-boson mixture (^{171}Yb-^{174}Yb) as well as boson-boson mixtures (^{172}Yb-^{174}Yb and ^{176}Yb-^{174}Yb). The time sequence of the transfer is also shown in Fig. 2. After compressing the cloud of the isotope mixture by raising the MOT magnetic field gradient, we irradiated the MOT cloud with the FORT beam. During a period of about 100 ms, both the MOT and FORT beams were turned on, and fractions of the atoms of both isotopes were successfully loaded into the FORT. Figure 3 shows typical images of simultaneous trapped ^{171}Yb and ^{174}Yb. One can clearly recognize that the atom distributions of the fermionic and bosonic isotopes in the trap were almost identical. We optimized the strength of the sideband, the MOT beam

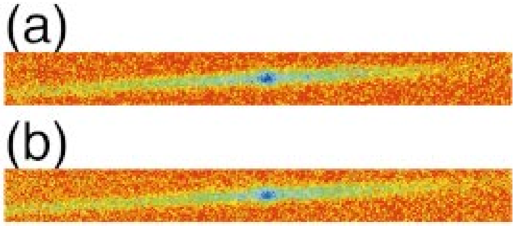

FIG. 3. (Color) Absorption images of ^{171}Yb atoms (a) and ^{174}Yb atoms (b) in the fermion-boson mixture trapped in the crossed FORT. Optical density increases from red to blue. Blue areas near the center of the image are crossed FORT regions. Yellow long areas from side to side are single FORT regions. The dimension of each picture is 180 μm×1710 μm.

power, and the loading durations of these two isotopes to make equal both numbers. Then the number of each isotope reached about 1×10^6. In the cases of boson-boson mixtures, the numbers of both isotopes were 8×10^5 for ^{172}Yb-^{174}Yb, and were 3×10^5 for ^{174}Yb-^{176}Yb, respectively. For all mixtures, the temperature was about 100 μK, which was measured by the time-of-flight method. The lifetimes of the trapped atoms were about 400 ms, which was mainly limited by the background vapor pressure of the order of 10^{-9} Torr. From the measured temperatures, atom numbers, and trap oscillation frequencies, we estimated the atom densities to be more than 10^{14}/cm^3 at the crossing region.

With the fermion-boson mixture (^{171}Yb-^{174}Yb) trapped by the crossed FORT, we could observe the first direct evidence of cross collisions between bosons and fermions trapped in any optical trap. First, we tried evaporative cooling in which the potential depth was decreased gradually by reducing the FORT laser light intensity with an AOM inserted in the FORT laser beam path. Initially, the FORT potential depth was 1090 μK, which was kept for 30 ms. In the next 10 ms, the potential depth was linearly decreased from 1090 μK to 700 μK, then from 700 μK to 61 μK in 50 ms, and finally from 61 μK to 25 μK in 80 ms. It is noted that we have recently demonstrated that this scheme really worked for bosons ^{174}Yb and resulted in the successful cooling from 100 μK to 4 μK, although the phase-space density (PSD) did not increase so much in our configuration [20]. However, in the case of fermions ^{171}Yb, starting with 8×10^5 ^{171}Yb atoms in the crossed FORT, we have found that all the atoms escaped from the crossed FORT at the end of this sequence. The failure of the evaporative cooling for the fermions ^{171}Yb should be attributed to slow thermalization due to the small elastic collision rate between cold fermions. Then we tried sympathetic cooling in the mixture of fermions ^{171}Yb and bosons ^{174}Yb. Initially, the mixture was composed of 1×10^6 ^{171}Yb atoms and 7×10^5 ^{174}Yb atoms. After the scheme mentioned above, we observed that 2×10^4 ^{171}Yb atoms were still remaining in the trap. Although we could not measure the atom temperature because of the small atom number, it was certainly below the trap potential of 25 μK. It should be noted that our observation did not show a successful *evaporative cooling* of fermions ^{171}Yb even in the case of mixture, i.e., PSD did not increase with ramping down the potential. However, the PSD really increased in the case of the mixture compared with that of pure fermions, which is direct evidence of a *sympathetic cooling* effect. In this experiment, we took special care to avoid instrumental effects. Even in the measurement for the pure fermion ^{171}Yb gas, we performed exactly the same experimental procedures as those for the mixture except for closing the atomic beam shutter during the loading of the bosons ^{174}Yb. Consequently, the observed difference between the mixture and the pure fermion gas truly comes from collision between bosons ^{174}Yb and fermions ^{171}Yb.

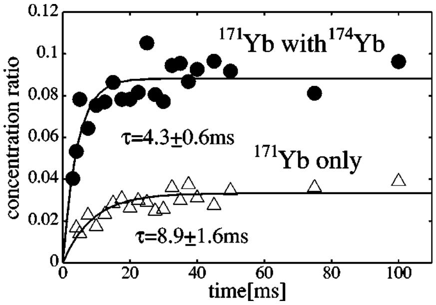

FIG. 4. Time evolution of the ^{171}Yb concentration ratio with (●) and without (△) ^{174}Yb, after switching on the crossed FORT. The concentration ratio was defined as the atom number in the crossed FORT region relative to the atom number in the whole FORT region. The solid lines show exponential fits to the measured data, and τ indicates the time constant. The observed time scales for loadings are close to the period of the axial oscillation of the single FORT.

To observe clearly the effect of the cross collisions between ^{171}Yb and ^{174}Yb, we used a scheme of ''delayed crossed FORT'' [14]. In this scheme, the atoms were initially trapped in a ''single FORT,'' by blocking the second FORT beam with an mechanical shutter. By opening the shutter after a certain delay time, we suddenly produced a deep and narrow well potential in the single FORT potential. This delayed crossed FORT experiment is similar to the adiabatic deformation experiment, in which atoms can be compressed by producing adiabatically a small and steep potential in a large and shallow trap [22]. When two atoms trapped in single FORT collide in the crossing region, one atom is excited to a higher vibrational level, and the other atom decays to the lower level in the crossed FORT. This process results in the increase of the atoms in the crossing region. It is noted that, in this scheme, the loading into the crossing region was purely ascribed to the atom-atom elastic collisions since the MOT beams were completely turned off before the crossed FORT potential was produced. Therefore, the concentration in the crossed region represents a direct probe of elastic collisions between trapped atoms. The time evolution of the ^{171}Yb atom distribution in the crossed FORT is shown in Fig. 4 for the mixture of fermions ^{171}Yb and bosons ^{174}Yb and for the pure fermion gas of ^{171}Yb atoms. Here, we have introduced a ''concentration ratio'' defined as a ratio of the number of atoms trapped only in the crossing region to the total number of trapped atoms. After 100 ms from opening the shutter, a concentration ratio for the mixture reached about 0.08, which is considerably large compared with the value of about 0.03 for the pure fermion gas.

The above-mentioned phenomena can be understood as follows. The small concentration ratio in the pure fermion gas can be explained by the small collisional cross section of cold ^{171}Yb which is expected when the temperature is below the *p*-wave centrifugal barrier because of the lack of *s*-wave scattering for identical fermions. In the case of the mixture, the observed enhancement of the loading of fermions ^{171}Yb into the crossing region should be attributed to the enhanced thermalization of fermions ^{171}Yb through collisions (e.g., *s* wave) between the bosons ^{174}Yb and the fermions ^{171}Yb.

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