PHYSICAL REVIEW A VOLUME 59, NUMBER 2 FEBRUARY 1999

Magneto-optical trapping of Yb atoms and a limit on the branching ratio of the $^1P_1$ state

K. Honda, Y. Takahashi,* T. Kuwamoto,† M. Fujimoto, K. Toyoda,
K. Ishikawa, and T. Yabuzaki
Department of Physics, Faculty of Science, Kyoto University, Kyoto 606-8502, Japan

(Received 18 August 1998)

We have succeeded in magneto-optical trapping of Yb atoms decelerated by a Zeeman slower method. The number of the trapped atoms is more than about 1.3×10^6 measured by light absorption. We have found the evidence of the branching from the $^1P_1$ excited state to triplet states, and determined the lower limit on the branching ratio to be 1.2×10^{-7}. [S1050-2947(99)51002-0]

PACS number(s): 32.80.Pj, 32.70.Fw, 42.50.Vk

Recently gaseous Yb atoms have attracted much interest in various respects. An optical resonance of the $^1S_0\leftrightarrow{}^3P_1$ intercombination transition has been a model system for studying quantum optics [1]. Figure 1 shows the energy-level diagram. The forbidden transition $^1S_0\leftrightarrow{}^3P_2$ is proposed as an optical frequency standard [2]. The tests of the symmetrization postulate and the Pauli exclusion principle using Yb atoms have also been proposed [3]. The enhanced parity violation effect is predicted for $^1S_0\leftrightarrow{}^3D_1$ transition [4]. The usefulness of Yb atoms in the search for an atomic electric dipole moment, the existence of which indicates violation of time-reversal symmetry [5], is also pointed out [6].

So far, most of the experiments and experimental proposals with Yb atoms have been made for an atomic beam or an optogalvano cell. Since high density, low temperature, and the controllability of laser-cooled and trapped atoms are also great advantages in these experiments and proposals, laser cooling and trapping of Yb atoms are very important. Recently the deceleration and velocity control of the Yb atomic beam have been reported by Watanabe *et al.* [7] with the broadband pulse laser, and the double-resonance experiments by Ohmukai *et al.* [8].

However, the possibility of large branching ratios between the decays from the $^1P_1$ state to triplet states and the decay from the $^1P_1$ state to the $^1S_0$ state was pointed out [9], which causes great difficulty in a magneto-optical trap (MOT) of Yb. Thus, we desire to clarify whether the MOT of Yb atoms can be successfully performed with the $^1P_1\leftrightarrow{}^1S_0$ transition or whether the branching from the $^1P_1$ excited state is fatally large, in order to get a long trapping time of the MOT. In the present paper, we report on our experiment of laser cooling and trapping of Yb atoms. The Yb atomic beam was first decelerated by a Zeeman slower method using the singlet transition $^1S_0\leftrightarrow{}^1P_1$, and then loaded into MOT. So far we have been able to obtain a trapping time of about 200 ms that is long enough for the MOT. The number of the trapped atoms was more than about 1.3×10^6, which was measured by light absorption. Furthermore, we found evidence of the branching from the $^1P_1$ excited state to triplet states, and determined the lower limit of the branching ratio of the excited $^1P_1$ state by measuring the intensity ratio between the fluorescence due to the transition $^3P_1\rightarrow{}^1S_0$ and that due to $^1P_1\rightarrow{}^1S_0$.

We performed experiments in several different configurations of the chambers, laser beams, and magnetic fields for a Zeeman slower and the MOT. The experimental results, however, did not show any essential difference. In Fig. 2 the top view of one of the vacuum chambers we used is shown. The Yb oven was located inside the right part of the chamber evacuated by a turbomolecular pump (300 l/s). We normally set the temperature of the oven at 623 K where the saturated vapor pressure is 5×10^{-6} torr. We used natural Yb metal, including seven stable isotopes of Yb. A hole of 1 mm diameter at the exit of the oven and that of 5 mm in the mirror located inside the chamber defined the atomic beam. The left side of the chamber is the high-vacuum part for the MOT evacuated by an ion-pump (200 l/s) to maintain the pressure at less than 1×10^{-8} torr. A rather large flux could be expected due to the short distance (39 cm) between the oven and the MOT region, which became possible owing to the short lifetime of the $^1P_1$ state (5.5 ns). Fluorescence from

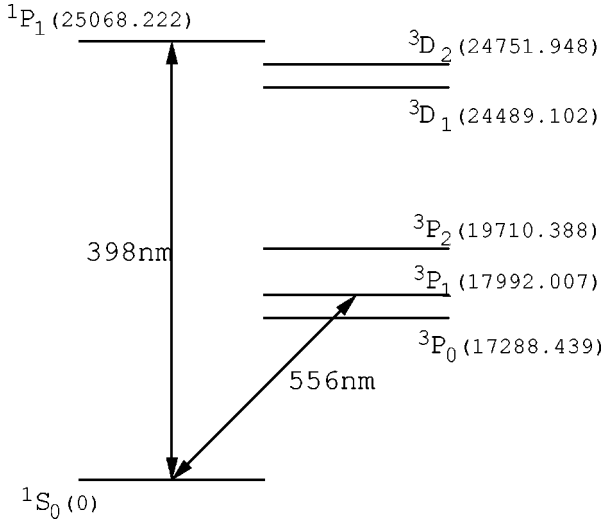

FIG. 1. Energy-level diagram of Yb. The numbers in parentheses represent the energy in cm^{-1}. The singlet transition $^1S_0\leftrightarrow{}^1P_1$ of 398 nm is used for laser cooling. The fluorescence from the $^3P_1$ state to the $^1S_0$ state is detected in the measurement of the branching ratio.

*Author to whom correspondence should be addressed. Electronic address: yitk@scphys.kyoto-u.ac.jp

†Present address: Department of Physics, Faculty of Science, Hiroshima University, 1-3-1 Higashi Hiroshima 739-8526, Japan.

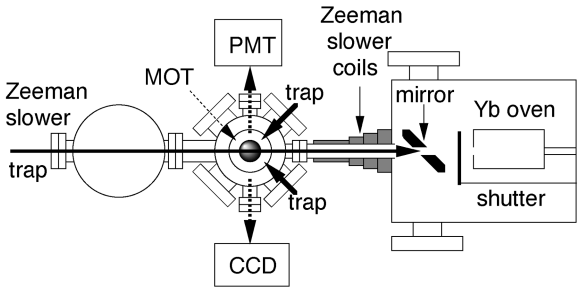

FIG. 2. Experimental setup. The 398-nm laser beams were irradiated to the atoms for the Zeeman slower and the MOT. The fluorescence from the MOT was detected by a CCD camera or a photomultiplier tube (PMT). A mirror with a hole for an atomic beam was set inside a chamber. The right side of the chamber was evacuated with a turbopump, the left with an ion pump.

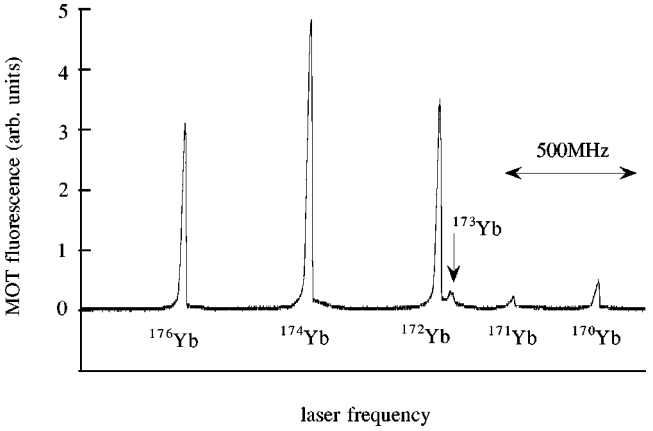

FIG. 3. Intensity of fluorescence from the MOT as a function of the laser frequency. The resonance positions are also indicated.

the MOT region was detected by a charge-coupled-device (CCD) camera and a photomultiplier tube.

For the excitation of the $^1S_0 \leftrightarrow {}^1P_1$ transition, about 100 mW of 398-nm light was obtained after resonant frequency doubling of more than 1 W of power of a ring Ti:sapphire laser at 796 nm. Because the saturation intensity (I_s) of this transition is 60 mW/cm^2, more power was preferable. The frequency of the Ti:sapphire laser was locked to a reference cavity that was stabilized to a Rb saturated absorption line through a diode laser. The 398-nm output was divided into beams, one for Zeeman slower and the others for the MOT. The beam for a Zeeman slower was also used as one of the trapping beams. The power of each beam was about 20 mW and the beam diameter about 1 cm at the MOT region. It is noted that the beam for a Zeeman slower became narrower near to the Yb oven in accordance with the divergence of the atomic beam. An optogalvano cell was used to monitor the resonance condition.

The Zeeman slower we used was a standard decreasing field type with σ^+ circularly polarized light. A pipe of 20 cm length connecting the left and right sides of the chambers was wound by 1.5-mm ϕ copper wire to produce the magnetic-field gradient with which an atom with initial velocity smaller than 330 m/s could be stopped with a laser beam of a saturation intensity. A set of anti-Helmholtz coils for the MOT was placed at the end of the Zeeman slower coils. A current of 10 A in these MOT coils could produce a field gradient of about 70 G/cm in the axial direction.

By changing the trap laser frequency we succeeded in observing the MOT of all the isotopes, except for ^{168}Yb among seven naturally abundant isotopes, which could be easily recognized by a CCD camera. Figure 3 shows the PMT signal of fluorescence from the MOT as a function of the laser frequency. One can recognize six peaks corresponding to the six isotopes. The asymmetry of each peak is also recognized, which shows clearly that the MOT was effective in the red detuning. The diameter of the trapped atom cloud was typically 2.5 mm. Since the even isotopes have no nuclear spin, the associated energy levels are very simple and suitable for the Zeeman slower and the MOT. The ratios of the observed signal intensities of the even isotopes were close to those of natural abundances. The failure of the detection of the MOT for ^{168}Yb was due to the extremely small natural abundance (0.13%). On the contrary, the signals of ^{171}Yb and ^{173}Yb were weaker than the others, in spite of the relatively large abundances (14.3% for ^{171}Yb and 16.1% for ^{173}Yb). Since ^{171}Yb and ^{173}Yb have nuclear spins of 1/2 and 5/2, respectively, the hyperfine structures in the excited $^1P_1$ state and the optical pumping in the ground $^1S_0$ state would be the origin of the relative weakness of the signals. All the measurements described hereafter were done for ^{174}Yb atoms, since this isotope has the largest natural abundance (31.8%), and so gave the largest signals. The detuning of the laser that was used in the remaining measurements was about half of the natural linewidth Γ ($\Gamma = 2\pi \times 29$ MHz).

The density and number of the trapped atoms were determined by the absorption measurement of a 398-nm probe light produced by a frequency doubling of another Ti:sapphire laser. Since the frequency stability of our probe laser was not good enough for the usual transient absorption measurement after turning off the trapping beams, we performed a steady-state absorption measurement. The probe light was continuously irradiated to the atom cloud and the frequency was scanned across the resonance while the trapping beams remained on during the measurements. For this method it is important to estimate the saturation effect due to the trapping laser beams. Based on a simple two-level theory, the detuning of $\Gamma/2$ and the intensity $I = 2I_s$ give the excited-state population of 1/4. So far we have observed about 9% absorption. Therefore, we can say that the density was about 1.6×10^8 cm^{-3} and the total number of the trapped atoms about 1.3×10^6 at least, and these numbers should be multiplied by 2, based on the above estimation of the saturation effect.

We tried to estimate the temperature of the trapped atoms by measuring the excitation spectrum of the $^1S_0 \leftrightarrow {}^3P_1$ (556-nm) line, instead of the usual time-of-flight method. The linewidth of this line is as narrow as about 180 kHz; thus, in principle, we can know the temperature directly by measuring a Doppler width of this line, unless the temperature is as low as several μK. We observed the $^1S_0(m_J = 0) \leftrightarrow {}^3P_1(m_J = 0)$ line, since this is insensitive to magnetic fields. Since our probe dye laser could not be scanned fast enough for the transient excitation measurement after turning off the trapping beams, the measurement was performed in the steady-state condition. The trapping beams remained on during the measurement and the probe dye laser frequency was scanned slowly. The observed spectrum had about 7

MHz full width at half maximum (FWHM), and this width could be explained by the Autler-Townes effect due to the trapping beams. So the trapped atom would be much colder than the temperature, which corresponds to the Doppler width of 7 MHz FWHM.

We measured the decay time of the number of the trapped atoms. A fluorescence of 398 nm was monitored after turning off the atomic beam by a mechanical shutter in front of the atomic oven. So far, a decay time of about 200 ms has been observed. It depended on the trap laser alignment and detuning. The loading time, measured by suddenly turning on the atomic beam by the mechanical shutter, was also about 200 ms, which is consistent with the decay time measurement. This decay time is rather short to be considered as the one due to the collision with background gases of about 10^{-8} torr. The decay due to the light-assisted collision would also be negligible for the atom density of the present experiment.

While we have succeeded in the magneto-optical trapping of Yb atoms with 398-nm light in spite of the possibility of a fatally large branching from the $^1P_1$ state, it is important to obtain information on the branching that would ultimately limit the trapping time. The calculation of the branching ratios between the decays from the $^1P_1$ state to triplet states and the decay from the $^1P_1$ state to the $^1S_0$ state was reported in Ref. [9]. The result has, however, a large uncertainty ranging from 10^{-6} to 10^{-9}. Here we investigated experimentally the branching ratio by using the trapped atoms.

The atoms in the $^1P_1$ state are expected to decay to the triplet $^3D_2$ ($24\,752\,\mathrm{cm}^{-1}$) and $^3D_1$ ($24\,489\,\mathrm{cm}^{-1}$) states and the $(7/2,3/2)_2$ ($23\,189\,\mathrm{cm}^{-1}$) state. The atoms in the $^3D_1$ and $^3D_2$ states decay to the lower $^3P_{0,1,2}$ states with lifetimes of 100 ns and 120 ns, respectively [10]. The atoms in the $^3P_1$ state decay to the ground state with a lifetime of 875 ns and can again get into the cooling cycle, whereas the other two states $^3P_0$ and $^3P_2$ are metastable, and so the atoms in these states rarely return to the ground state and finally escape from the trap. Since all the transitions from the $^1P_1$ state to the $^3D_{1,2}$ and $(7/2,3/2)_2$ states and those from $^3D_{1,2}$ to $^3P_{0,1,2}$ are in the far-infrared and infrared regions, which are hard to detect, we observed the 556-nm fluorescence from the $^3P_1$ state to the $^1S_0$ state. This measurement does not determine the exact value of the branching ratio, but is only sensitive to those channels in which the atoms finally decay to the $^3P_1$ state. From this measurement we could determine the lower limit of the overall branching ratio. To deduce the overall branching ratio from the 556-nm fluorescence measurement, we must know the relative transition probabilities from the $^1P_1$ state to the $^3D_{1,2}$ and $(7/2,3/2)_2$ states and also those from the $^3D_{1,2}$ states to the $^3P_{0,1,2}$ states [4].

Note that what we measured was the ratio of the 556-nm fluorescence ($^3P_1 \rightarrow {}^1S_0$) to the 398-nm fluorescence ($^1P_1 \rightarrow {}^1S_0$) in the presence of 398-nm light beams alone. The weak 556-nm fluorescence as well as the strong 398-nm fluorescence were detected with a highly sensitive CCD camera cooled by liquid nitrogen through a monochromator. With a standard lamp we calibrated the relative sensitivities at 398 nm and 556 nm of the whole detection system, including the chamber window, collecting lenses, mirrors, and the monochromator, as well as the CCD camera.

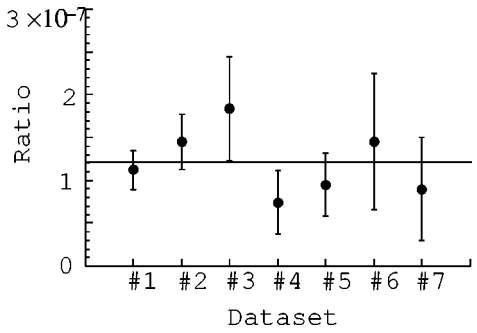

FIG. 4. Plot of the ratios between the count rates of 398-nm and 556-nm fluorescence. Each dataset corresponds to a different configuration of experiments. The fluorescence was detected with a highly sensitive CCD camera cooled by liquid nitrogen through a monochromator. The numbers shown in this figure were already compensated for by the different sensitivities at 556 nm and 398 nm of the detection system. Seven datasets had different measurement uncertainties expressed by the error bars. The horizontal line indicates the average of these data.

The measurement was performed using the laser-cooled atoms. An atom as fast as 10 m/s, which corresponds to the temperature of about 1 K, runs 100 μm in 10 μs which is long enough compared with the lifetimes of the $^3D_{1,2}$ and $^3P_1$ states. Since the distance of 100 μm around the center of the MOT was well within our fluorescence detection region, we could assure that we did not lose the 556-nm fluorescence at all if we used the laser-cooled atoms. In addition, the laser-cooled and trapped atoms were free from a wall collision that might cause a nonradiative decay from the $^1P_1$ state to the other states, which is also a merit in the measurement of a weak branching.

Figure 4 shows the plots of the ratios between the count rates of 398-nm and 556-nm fluorescence. In order to check possible systematic effects we performed the measurements with different conditions of the experimental parameters such as the current for the MOT. No correlation with the change of the experimental parameters was recognized, and a different configuration simply led to a different number of trapped atoms.

From Fig. 4 we determined the ratio of the 398-nm and 556-nm fluorescence to be 1.21×10^{-7}, with a standard deviation of 0.39×10^{-7}. This sets a lower limit of the branching ratio, and also means that the trapped atoms decay to the $^3P_1$ state with a time constant of about 274 ms when the atoms are irradiated with 398-nm laser beams that are off-resonant by half of the linewidth and have a saturation intensity. It is impressive that this time constant is almost the same as the observed MOT decay time.

In summary, we carried out the magneto-optical trapping of the Yb atoms decelerated by a Zeeman slower method. The number of the trapped atoms was more than about 1.3×10^6 measured by light absorption. We confirmed the existence of the branching from the $^1P_1$ excited state to the triplet states, and measured the intensity ratio between the fluorescence $^3P_1 \rightarrow {}^1S_0$ and $^1P_1 \rightarrow {}^1S_0$ to be 1.2×10^{-7}.

To further increase the number of the trapped atoms, we have started two kinds of experiments. One is to repump the atoms in the metastable states $(7/2,3/2)_2$ and $^3P_{0,2}$. By using a diode laser tuned to the $^3P_2 \leftrightarrow {}^3S_1$ transition (770 nm) and

a dye laser tuned to $^3P_0 \leftrightarrow {}^3S_1$ (649 nm), the atoms are pumped into the $^3P_1$ state, from which the atoms are returned to the ground $^1S_0$ state with a radiative lifetime of about 1 μs and can participate in the cooling cycle again. The atoms in the $(7/2,3/2)_2$ state can be repumped by exciting the $(7/2,3/2)_2 \rightarrow {}^1D_2$ (40062 cm^{-1}) transition (593 nm). Another kind of experiment is the use of the intercombination transition $^1S_0 \leftrightarrow {}^3P_1$ for the MOT, while in the Zeeman slower the singlet $^1S_0 \leftrightarrow {}^1P_1$ is used. The intercombination line is a closed system without any branching and so is appropriate for obtaining a long trapping time. In the Zeeman slower, on the contrary, the strong radiation pressure provided by the singlet transition is needed. For this purpose, the Zeeman slower of the increasing magnetic-field type using σ^- circularly polarized light [11] is appropriate since the slowing laser becomes far-off-resonant to the slow atom in the weak magnetic field in the MOT region. The MOT with the intercombination line has another advantage in that the Doppler-limit temperature is as low as about 4 μK.

We acknowledge useful advice and discussions with M. Watanabe and R. Ohmukai. This work was partially supported by a Grant-in-Aid for Specially Promoted Research of Ministry of Education, Science, Sports and Culture of Japan (Grant No. 07102011).

[1] For example, A. M. Bacon, H. Z. Zhao, L. J. Wang, and J. E. Thomas, Phys. Rev. Lett. **75**, 1296 (1995); D. J. Heinzen, J. J. Childs, J. E. Thomas, and M. S. Feld, *ibid.* **58**, 1320 (1987).

[2] J. Hall, M. Zhu, and P. Buch, J. Opt. Soc. Am. B **6**, 2194 (1989).

[3] D. E. Kelleher, J. D. Gillaspy, and K. Deilamian, in *Laser Spectroscopy IX. Proceedings of the Ninth International Conference on Laser Spectroscopy*, edited by M. S. Feld, J. E. Thomas, and A. Mooradian (Academic, Boston, 1989), p. 332; K. Deilamian, Ph.D dissertation, University of Wisconsin–Madison, Madison, WI, 1991 (unpublished).

[4] D. DeMille, Phys. Rev. Lett. **74**, 4165 (1997). In this paper the calculated relative transition probabilities from $^3D_1$ were reported.

[5] See, for example, I. B. Khriplovich and S. K. Lamoreaux, *CP Violation Without Strangeness, Electric Dipole Moments of Particles, Atoms, and Molecules* (Springer-Verlag, Heidelberg, 1997).

[6] Y. Takahashi, M. Fujimoto, T. Yabuzaki, Angom Dilip Singh, Manoj K. Samal, and B. P. Das, in *Proceedings of CP Violation and its Origin*, edited by K. Hagiwara (KEK Reports, Tsukuba, 1997).

[7] M. Watanabe *et al.*, J. Opt. Soc. Am. B **13**, 2377 (1996).

[8] R. Ohmukai *et al.*, Appl. Phys. B: Lasers Opt. **64**, 547 (1997).

[9] J. Migdalek and W. E. Baylis, J. Phys. B **24**, L99 (1991).

[10] C. J. Bowers *et al.*, Phys. Rev. A **53**, 3103 (1996).

[11] T. E. Barrett *et al.*, Phys. Rev. Lett. **67**, 3483 (1991).