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# Magneto-optical trapping of Yb atoms using an intercombination transition

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We report the magneto-optical trapping of ytterbium atoms using the $6s^2\,{}^1S_0$-$6s6p\,{}^3P_1$ intercombination transition. The magneto-optical trap is continuously loaded from an atomic beam decelerated by a Zeeman-tuned atomic-beam slower operated at the $6s^2\,{}^1S_0-6s6p\,{}^1P_1$ transition. Among seven stable isotopes of ytterbium, six isotopes of ${}^{170}$Yb, ${}^{171}$Yb, ${}^{172}$Yb, ${}^{173}$Yb, ${}^{174}$Yb, and ${}^{176}$Yb are successfully trapped. The number and density of the trapped atoms are about $10^8$ and $10^{11}\ \mathrm{cm}^{-3}$, respectively. The temperature of atoms is estimated to be about 20 $\mu$K from the time-of-flight measurement. The decay time of the trapped atoms after stopping the loading of atoms is about 3 s. [S1050-2947(99)50208-4]

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There has been much interest in atomic ytterbium (Yb) as an ideal sample for studying quantum optics [1,2]. Furthermore, the potential applications of Yb atoms include a test of spin statistics [3], an atomic frequency standard [4,5], and tests of the standard model of electroweak interactions [6,7].

It is expected that laser cooled and trapped Yb atoms will be extremely useful in many of these studies mentioned above because of the high density, low temperature, and controllability. Quite recently, a magneto-optical trapping (MOT) of Yb atoms was successfully carried out [8], where the singlet ${}^1S_0$-${}^1P_1$ transition (399 nm) was used for the MOT as well as the Zeeman slower. Figure 1 shows the energy-level diagram of Yb. A strong radiation pressure with this transition was quite useful for the Zeeman slower and the MOT. The MOT loading time was, however, as short as about 200 ms, mainly determined by the branching from the ${}^1P_1$ state to the metastable triplet states, which limited the trapped atom number to an order of $10^6$. The limitation on the atom number in a MOT due to the branching (optical pumping) is a common problem for the MOT of atomic species like alkaline-earth atoms [9,10] that have energy-level schemes similar to that of Yb.

In this paper, we report on the success of a MOT of Yb atoms using the weak ${}^1S_0$-${}^3P_1$ intercombination transition (556 nm). A great advantage of the MOT with the intercombination transition is that it is free from a loss of an atom number due to the branching. The MOT could be *continuously* loaded from an atomic-beam slowed by a Zeeman tuning method using the strong ${}^1S_0$-${}^1P_1$ singlet transition. Since the laser beam for the Zeeman slower in an increasing magnetic field configuration was far off-resonant for the atoms in the MOT, the trapped atoms were almost free from the affect of the Zeeman slower beam. With this successful combination of the weak and strong transitions in different roles, a two-orders-of-magnitude increase of the trapped atom number was achieved compared with that obtained using the singlet transition only. It is noted that this advantageous feature was not exploited in the very recent work on the MOT of Sr atoms using the intercombination transition [10].

Before we describe details of our method in the following, let us mention other advantages of the MOT using the intercombination transition. Owing to the narrow linewidth of the transition, the Doppler-cooling limit temperature $T_D$ is very low. This was impressively demonstrated in the MOT of Sr atoms by Katori *et al.* [10], where a temperature of about 400 nK was achieved using the ${}^1S_0$-${}^3P_1$ transition of Sr. The radiation trapping effect that usually limits the maximum density of the MOT was also reduced considerably due to the narrow linewidth of the intercombination transition of the Sr atoms. These advantages resulted in a high phase-space density of $10^{-2}$ by optical means alone. It is obvious that the MOT of Yb atoms using the intercombination transition also enjoys these advantageous features in temperature and density, although not so significantly as that of Sr atoms, due entirely to the different lifetimes of the ${}^3P_1$ states (875 ns for Yb and 21 $\mu$s for Sr).

Figure 2 shows the experimental setup around an atomic oven, a Zeeman slower, and a MOT. A Yb metal with natural abundance was vaporized in an oven with an orifice of 1-mm diameter. The oven was typically operated at a temperature of 623 K where the saturated vapor pressure was $5\times10^{-6}$ torr, and was evacuated by a turbomolecular pump (300 $l$/s). The aperture with a 5-mm diameter was located at a distance of 70 mm from the oven in order to align the atomic beam. A Zeeman slower was designed in an increas-

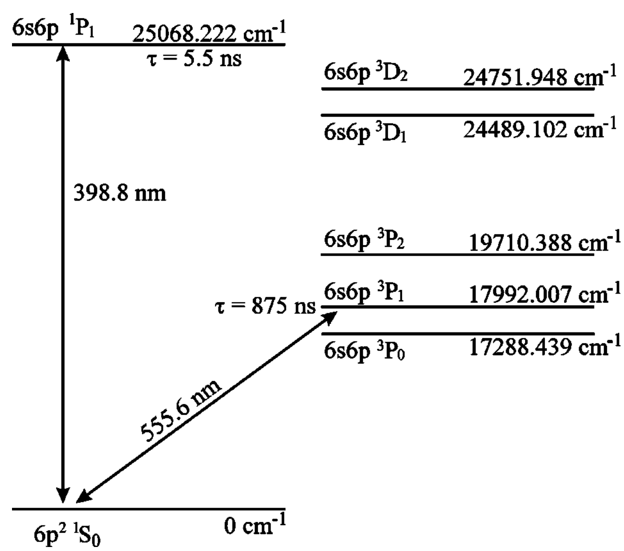


FIG. 1. Energy-level diagram of Yb related to the cooling and trapping in this work. Several physical properties are also shown.

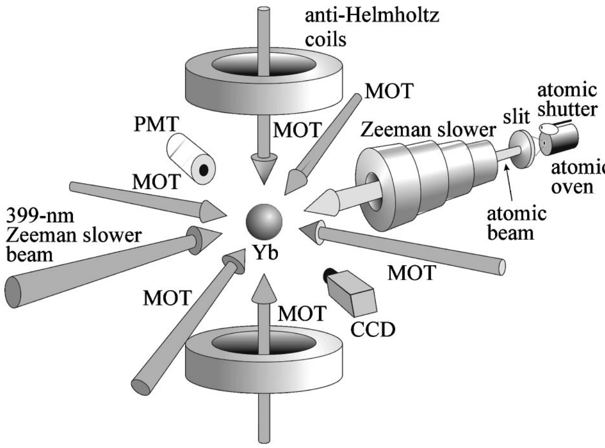


FIG. 2. Schematic view of the experimental setup of Zeeman-tuned atomic-beam slower and the magneto-optical trap of Yb atoms.

ing magnetic-field configuration [11]. The coil for the Zeeman slower was made of a 1.5-mm-diam copper wire, and was wound on a 20 cm-long stainless-steel pipe with a 16-mm inner diameter. The atoms with initial velocity smaller than 300 m/s can be stopped in this short distance for the Zeeman slower, using the 399-nm laser light with a saturation intensity of 60 mW/cm$^2$. The anti-Helmholtz coils behind the Zeeman slower produced a field gradient for the MOT. To compensate for the tail of the magnetic field of the Zeeman slower at the MOT point, an additional coil was placed on the opposite side of the MOT (left-hand side of Fig. 2). The MOT region was evacuated by an ion pump (200 $l$/s), and the pressure was less than $10^{-8}$ torr. Figure 3 shows the total magnetic field along the axis of the atomic beam produced by the Zeeman slower coil, the anti-Helmholtz coils for MOT, and the compensation coil. The frequency of the 399-nm laser for the Zeeman slowing was far detuned from the resonance ($\sim$660 MHz), which was indispensable for the MOT using the weak ${}^1S_0$-${}^3P_1$ transition. Otherwise, a near-resonant 399-nm laser light would have placed strong radiation pressure on the trapped atoms and also would have caused the branching effect.

The 399-nm laser beam for the Zeeman slower was obtained by resonant frequency-doubling of a cw ring Ti:sapphire laser operated at the wavelength of 798 nm. About 100 mW of 399-nm light was produced with the Ti:sapphire laser of 1-W power. The 399-nm laser beam had a 20-mm diameter at the MOT region, and was focused to a 1-mm diameter at the atomic oven, in accordance with the divergence of the atomic beam. A cw ring dye laser with R110 dye was used to produce 556-nm beams for the MOT. Each beam for the MOT had a power of about 10 mW and the diameter of about 20 mm. For stable operation of the MOT and Zeeman slower, frequency stabilizations of the two ring lasers were needed. We locked both laser frequencies to a temperature-stabilized reference cavity, with variable frequency offsets provided by acousto-optic-modulators (AOMs). The reference cavity was also stabilized to a Rb saturated absorption line through a diode laser. Furthermore, the dye laser frequency was narrowed from about 3 MHz to less than about 200 kHz with another AOM outside the laser cavity. This narrowing was important since the full width at half maximum linewidth $\Gamma/(2\pi)$ of the ${}^1S_0$-${}^3P_1$ transition is as narrow as 182 kHz.

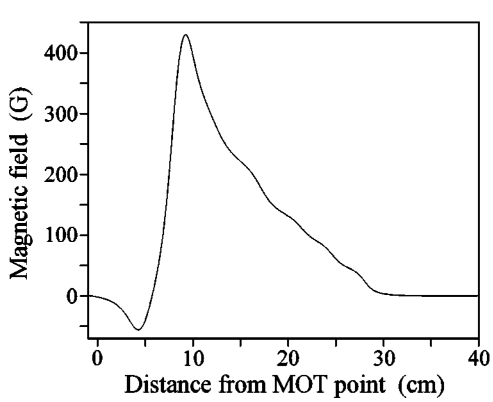


FIG. 3. Magnetic field along the axis of atomic beam produced by the Zeeman slower coil, the anti-Helmholtz coils and the compensation coil. The atomic beam comes from the right-hand side of this figure.

The frequencies of dye and Ti:sapphire lasers were monitored with a wavemeter when necessary, and the optogalvano cell was also helpful to roughly tune the dye laser frequency to a particular resonance of Yb atoms. In the present experiments, in addition, the dye laser should be near resonant to a particular resonance line at the MOT region, i.e., at $z=0$ in Fig. 3, with a precision of less than 1 MHz, while the frequency-doubled Ti:sapphire laser beam should be resonant to the singlet transition in the presence of a large magnetic field at $z=90$ mm in Fig. 3, also with about a 1-MHz precision. The typical procedure of the simultaneous tunings to different transitions with 1-MHz precision was as follows. First, we performed a cross-beam spectroscopy of the intercombination transition by observing the 556-nm fluorescence. The fluorescence was detected with a photomultiplier tube (PMT) and also with a charge-coupled-device (CCD) camera. Only the vertical laser beams for the MOT were used for this purpose. The resonance frequency could be determined from a peak in the excitation spectrum. Next, we turned on the 399-nm laser beam for the Zeeman slower. The resonance corresponding to the ${}^1S_0$-${}^1P_1$ transition in the presence of the large magnetic field at $z=90$ mm in Fig. 3 was obtained by observing the increase of the fluorescence at 556 nm as a result of the Zeeman slowing. Finally, all MOT beams at 556 nm were irradiated and the frequencies of two lasers were finely adjusted to give a large fluorescence signal from the MOT.

The radiation pressure provided by the intercombination transition is much weaker than that provided by the singlet transition. A detuning $\delta=\Gamma$ and an intensity $I=I_s$ are the standard condition for a MOT, where $I_s=0.14$ mW/cm$^2$ is a saturation intensity for the ${}^1S_0$-${}^3P_1$ transition. Under this condition, it was found from a semiclassical one-dimensional simulation that the velocity capture range was only about 2 m/s in an optimal field gradient of 2 G/cm along the atomic-beam direction. Here it was assumed that the Zeeman slowed beam would come along the axis displaced from the center of the MOT by a small distance, which was taken at 3 mm as a representative value for our experiment. The most difficult point in the design of the MOT with the intercombination transition is therefore how the MOT with the weak radiation pressure can catch a Zeeman-slowed atomic beam. It must be noted that too much slowing of the atomic beam with the Zeeman slower should be avoided, since it causes the explosion of the beam and results in a considerable reduction of the number of the atoms that can be loaded into the MOT. In our experiment, the distance between the MOT and the end of the Zeeman slower was 7 cm, which was designed to be as short as possible. The transverse heating during the Zeeman slowing was estimated to be about 1 m/s. So the Zeeman-slowed atoms must be much faster than about 7 m/s to reach the MOT capture region of about 1-cm radius without an explosion. This was actually confirmed by monitoring the velocity distribution of the Zeeman-slowed atoms that reached the MOT region through the fluorescence of a 556-nm probe laser irradiated along the direction, making an angle of 45° with the atomic beam. In order to capture the atoms faster than 7 m/s, which was still fast for the MOT with the weak intercombination transition in the standard condition, we utilized the trapping laser beam with multiple frequency components. Four frequency components at 600-kHz intervals were produced in the 556-nm trapping laser beam using the AOM driven by four radio-frequency components at the same interval. We tuned the laser frequency so that the highest frequency component among four should be slightly red-detuned, typically $\sim\Gamma$, from the exact resonance on the $^1S_0$-$^3P_1$ transition. The other three MOT beams could work as a part of the Zeeman slower in the field gradient of the MOT. In addition, each frequecy component had an intensity of about $10I_s$, so that even the atoms having resonance frequencies in between the sidebands could receive a considerable radiation pressure due to the power-broadening effect. For this laser beam with multiple frequency components, the velocity capture range is calculated to be 7 m/s for the intensity of $10I_s$ and the field gradient of about 5.2 G/cm along the atomic-beam direction. Under these experimental conditions we could have trapped many Yb atoms that were easily recognizable by the naked eye.

With the procedure described above, all the stable isotopes except $^{168}$Yb could be successfully trapped. Since the natural abundance of $^{168}$Yb is small, it was difficult to find the simultaneous resonances. However, we do believe that the MOT with the intercombination transition works similarly for this isotope. The intensity ratios of the observed fluorescence of the trapped atoms were close to those of natural sources. For the MOT and Zeeman slowing of $^{171}$Yb and $^{173}$Yb, the hyperfine levels of $F'=3/2$ and $F'=7/2$ in the excited $^3P_1$ state were used, respectively. During the Zeeman slowing, these odd isotopes were optically pumped into the $I_z=-1/2$ state for $^{171}$Yb in the ground $^1S_0$ state, and into the $I_z=-5/2$ state for $^{173}$Yb. In order for the optically pumped atoms to be successfully caught in the MOT, it was necessary to match the sense of the field gradient in the MOT with that in the Zeeman slower, as shown in Fig. 3. All the measurements mentioned hereafter were done for $^{174}$Yb, since it had the largest natural abundance of 31.8% and thus gave the largest signals.

It is noted that a weak radiation pressure of the 399-nm Zeeman slowing laser beam on the trapped atoms was recognized in some cases although the 399-nm laser beam was far-detuned from the resonance at the MOT region, typically by 660 MHz. However, by slightly misaligning the 399-nm beam so as not to directly irradiate the trapped atoms, this effect could be removed without sacrificing the performance of the Zeeman slowing.

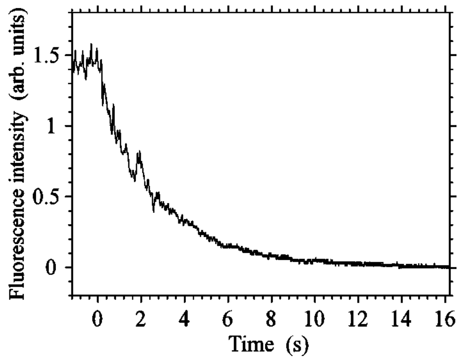


FIG. 4. Fluorescence intensity from the MOT of Yb atoms after turning off the atomic beam and Zeeman-slowing 399 nm laser beam. The atomic beam and the Zeeman slowing laser beam were turned off at $t=0$.

We could determine the number of trapped atoms from the fluorescence intensity counted with a calibrated PMT. Under optimum conditions the number of trapped atoms was about $10^8$. This is about two orders of magnitude larger than the number attained in the MOT using the singlet transition only [8]. This increase can be mainly attributed to the long trapping time of the MOT. The trapping time was measured by detecting the MOT fluorescence after the atomic beam and 399-nm laser light were simultaneously turned off in less than 1 ms with mechanical shutters. Figure 4 shows the decay of the fluorescence intensity from the trapped atoms as a function of time. The decay curve was well fitted to a single exponential curve. The obtained decay time was about 3 s, which is an order of magnitude longer than the value (about 200 ms) obtained in the MOT with the 399-nm transition. Thus, using the intercombination transition, we could overcome the branching problem that is inevitable in the MOT with the singlet transition. The loading time was also measured by suddenly turning on the atomic beam and the 399-nm laser. The result was consistent with the decay-time measurement. This value of the MOT decay is consistent with the collision-limited decay time calculated with the formula given by Bjorkholm [12] for a pressure of $10^{-8}$ torr.

The size of the trapped Yb atom cloud was measured by a CCD camera, and was less than 1 mm in diameter in a field gradient of 2.1 G/cm along the atomic-beam direction. The density of the trapped atoms was about $10^{10}$ cm$^{-3}$, which is also two-orders of magnitude larger than the value obtained in the MOT using the singlet transition [8]. Furthermore, by suddenly increasing the magnetic field gradient from 2.1 G/cm to 6.4 G/cm and simultaneously adjusting the trap laser frequency as in Ref. [13], we could achieve a much higher density of more than $10^{11}$ cm$^{-3}$. The radiation trapping effect that normally limits the maximum density in a MOT is expected to be considerably reduced due to the large inhomogeneous broadening of the absorption line compared with the homogeneous linewidth. A detailed study of this behavior is now underway.

The temperature of the trapped Yb atoms was measured by the time-of-flight (TOF) method. The probe laser beam having an elliptical cross section (10-mm width and 1-mm thickness) was placed 1.5 mm below the atom cloud. This probe beam was tuned near to the resonant frequency of the $^1S_0$-$^3P_1$ transition, and the fluorescence was detected by the PMT. The observed TOF signal was fitted to the function given by Weiss *et al.* [14]. We also performed a temperature measurement with a fluorescence imaging method. These two methods resulted in the same temperature of about 20 $\mu$K, which is higher than the Doppler-cooling limit of 4.4 $\mu$K. This rather high temperature was mainly because the intensity of the trapping laser beam was set to about $10I_s$ in order to obtain a sufficient velocity capture range of the MOT. One will be able to achieve the Doppler-limit temperature of 4.4 $\mu$K if one suddenly reduces the MOT beam intensity below the saturation intensity after collection of enough numbers of atoms. In addition, it will be interesting to see that the Sisyphus cooling, magnetic orientational cooling, and the Doppler-cooling mechanisms [15] can work in different manners for different isotopes of Yb atoms, due to the difference in nuclear spin. For even isotopes $(I=0)$, only the Doppler cooling is effective. For $^{171}$Yb with nuclear spin $I=1/2$, the Sisyphus cooling mechanism also works, but the magnetic orientational cooling does not. It is also interesting that the Sisyphus cooling limit might be higher than the Doppler cooling limit [16]. For $^{173}$Yb with nuclear spin $I=5/2$, all of the three mechanisms work.

In conclusion, we succeeded in the magneto-optical trapping of Yb atoms using the $6s^2\,{}^1S_0$-$6s6p\,{}^3P_1$ intercombination transition. The MOT could be continuously loaded from a Zeeman-tuned atomic-beam slower operated at the $6s^2\,{}^1S_0$-$6s6p\,{}^1P_1$ transition. Among seven stable isotopes of Yb, six isotopes of $^{170}$Yb, $^{171}$Yb, $^{172}$Yb, $^{173}$Yb, $^{174}$Yb, and $^{176}$Yb were successfully trapped. The number and density of the trapped atoms were more than $10^8$ and $10^{11}$ cm$^{-3}$, respectively. The temperature of atoms was estimated to be about 20 $\mu$K from the time-of-flight measurement. The decay time of the trapped atoms after stopping the loading of atoms was about 3 s. In the present work the experimental parameters were optimized to obtain a large number of atoms in the MOT. One will be able to obtain a lower temperature by suddenly changing the intensity and detuning of the trapping beams of the MOT. The technique demonstrated in the present paper would be also useful for the MOT of alkaline-earth atoms where a trapping time with a singlet transition was considerably limited by the existence of the branching from the excited $^1P_1$ state.

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