Inelastic Collisions in Optically Trapped Ultracold Metastable Ytterbium

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We report measurement of inelastic loss in dense and cold metastable ytterbium (Yb[$^3P_2$]). Use of an optical far-off-resonance trap enables us to trap atoms in all magnetic sublevels, removing m-changing collisional trap loss from the system. Trapped samples of Yb[$^3P_2$] are produced at a density of 2×10^{13} cm^{-3} and temperature of 2 μK. We observe rapid two-body trap loss of Yb[$^3P_2$] and measure the inelastic collision rate constant $1.0(3) \times 10^{-11}$ cm^3 s^{-1}. The existence of the fine-structure changing collisions between atoms in the $^3P_2$ state is strongly suggested.

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There is increasing interest in ultracold two-electron atoms [1,2], such as the alkaline earth metals (e.g., Ca and Sr) and Yb. In particular, novel characteristics of the metastable $^3P_2$ atoms have recently attracted attention, both for applications and for the study of their collisional properties [3]. These atoms are set apart from the more commonly studied alkali metal atoms because collisions between $^3P_2$ atoms are intrinsically anisotropic [4]. Recent theories have investigated the effects of this anisotropy, including its interplay with magnetic field effects, which enable novel control of the scattering length [5], and inelastic Zeeman relaxation collisions (m-changing collisions) due to a strong coupling among the partial waves of relative motion [6,7]. Also, the magnetic dipole-dipole interaction between $^3P_2$ atoms is 9 times larger than that between alkali metal atoms. This has led to theoretical predictions such as novel quantum phases and use in quantum information systems [8,9].

In order to move toward study of these new possible features, several laboratories have realized laser cooling and trapping of metastable two-electron atoms. Ca and Sr atoms decaying to the $^3P_2$ state from the $^1P_1$ state, which is the upper state in the $^1S_0 \leftrightarrow {}^1P_1$ magneto-optical trap (MOT) transition, have been successfully trapped in a magnetic trap [10]. Also, a MOT operating on the $^3P_2 \leftrightarrow {}^3D_3$ transition has been used to load a magnetic trap [11]. In spite of successes of these approaches, evaporative cooling of $^3P_2$ atoms in a magnetic trap to reach Bose-Einstein condensation (BEC) turned out to be unsuccessful due to trap loss caused by strong m-changing collision processes [6]. More recently, a similar large inelastic collision rate in Ca[$^3P_2, m_J = 2$] was observed [12].

The loss induced by m-changing collisions in a magnetic trap can be overcome by employing an optical far-off-resonance trap (FORT). As in Ref. [13], the FORT wavelength can be chosen so that atoms in every magnetic sublevel of the $^3P_2$ state can be trapped with the same strength. As a result, although m-changing collisions can still occur, which distributes the atoms over the different magnetic sublevels, they will not lead to trap loss. Thus, any trap loss observed in such a trap must be due to a different physical mechanism. Study of these collisional properties is crucial to understand the physics of these important class of atoms and states.

In this Letter, we report both the experimental realization of optical trapping (FORT) of ultracold ^{174}Yb[$^3P_2$] atoms at high atom number density and the quantitative measurement of inelastic collisions at ultralow temperature regime where only the s-wave scattering is responsible, which is the important difference from the previous works. In contrast to previous methods, we first trap atoms and perform evaporative cooling using Yb[$^1S_0$] in the FORT. We optically excite Yb[$^1S_0$] to the $^3P_2$ state to obtain ultracold trapped Yb[$^3P_2$], achieving a number density of 2×10^{13} cm^{-3} at a temperature of 2 μK with phase space density (PSD) of 5×10^{-3} for the most populated substate. Our newly achieved atom number density is larger than the previous work by an order of 3 [11]. We also measured a large two-body inelastic collision rate in the FORT which we interpret as fine-structure changing collisions in this ultracold temperature regime. Fine-structure changing collisions have played an important role in, for example, cooling and trapping of atoms with nonzero orbital angular momentum [14] and cooling of interstellar gas and planetary atmospheres [15]. Although fine-structure changing inelastic collisional properties have previously been investigated for Mg[^3P_j], O[^3P_j], Sc[^2D_j], and Ti[^3F_j] colliding with closed shell atoms [16–19], they had not been seen in collisions between $^3P_2$ atoms. While the recent experiment of magnetically trapped Ca atoms studied m-changing collisions between $^3P_2$ atoms and discussed the possibility of the fine-structure changing process [12], we believe that our work is the first definite experimental measurement of this process between $^3P_2$ atoms at ultracold temperature.

Our typical procedure to prepare and detect atoms in the $^3P_2$ state is summarized in Fig. 1. At the first stage A, we

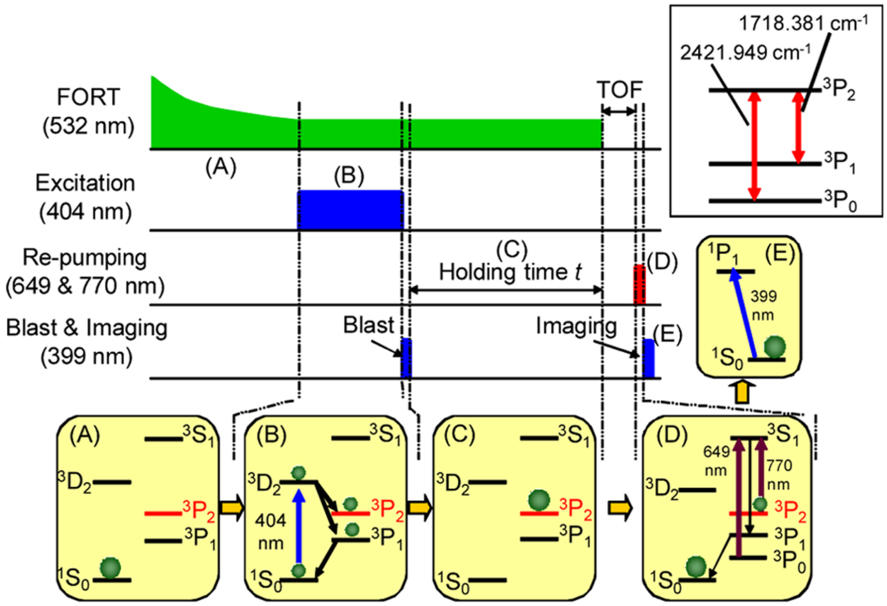

FIG. 1 (color online). Experimental procedures to excite atoms to the $^3P_2$ state. (a): Yb atoms trapped in a MOT are transferred to the FORT and cooled by evaporative cooling. (b): Then atoms are optically excited to the $^3P_2$ state in the FORT via the intermediate $^3D_2$ state and subsequent spontaneous decay $^3D_2 \rightarrow {}^3P_2$. Atoms remaining in the ground state are blew by a short blast laser pulse just after the excitation. (c): Metastable atoms are left in the FORT during the holding time t. (d): After a TOF time, metastable atoms are repumped to the ground state by 770 nm ($^3P_2 \leftrightarrow {}^3S_1$) and 649 nm ($^3P_0 \leftrightarrow {}^3S_1$) laser pulses of 100 μs and (e) detected by the absorption imaging. The inset shows the fine-structure separation.

prepare cold ^{174}Yb atoms in the ground state in the FORT by the same method as that of our previous works [20,21]. We typically collect 10^7 Yb atoms in the ground state by the MOT and transferred to a FORT created by focused diode-pumped solid state 10 W-laser at 532 nm. After carrying out evaporative cooling, we typically have 10^6 atoms at a temperature of 30 μK in the single FORT. When we use a crossed FORT configuration and perform evaporative cooling, a temperature of atoms reaches below 1 μK.

At the next stage B, we optically excite atoms to the $^3P_2$ state in the FORT. Atoms are first excited to the intermediate $^3D_2$ state [22] by a 404 nm stabilized laser [23] and spontaneously decay to the $^3P_2$ state with the lifetime 460 ns of the $^3D_2$ state. Although some atoms in the $^3D_2$ state can also decay to the $^3P_1$ state, they immediately decay to the ground state with the lifetime 875 ns of the $^3P_1$ state and are reexcited to the $^3D_2$ state. Thus, we can transfer all atoms to the $^3P_2$ state typically within 5 ms. The excitation laser is superposed with the FORT laser (see Fig. 2) and the peak intensity at atoms reaches 1.5 W/cm^2. Just after the excitation, we irradiate a short blast pulse which blows remaining atoms in the ground state by using the strong $^1S_0 \leftrightarrow {}^1P_1$ transition.

The $^1S_0 \leftrightarrow {}^3D_2$ transition (404 nm) is the electric quadrupole ($E2$) transition. In this experiment, as shown in Fig. 2, we set $\vec{e}_{404} \parallel z$ and $\vec{e}_k \parallel x$, where $\vec{e}_{404}$ and $\vec{e}_k = \vec{k}/|\vec{k}|$ are the polarization and the wave number unit vectors of the 404 nm excitation laser. Thus atoms are excited to the $^3D_2$, $m = \pm 1$ states due to the selection rule and subsequently decay to all the magnetic sublevels of the $^3P_2$ state with the ratio 3:1:2 for $|m| = 0$, 1, and 2 sublevels of the $^3P_2$ state, respectively.

At the stage C, we hold metastable atoms in the FORT for a time t. Then, at the stage D, we rapidly repump all the metastable $^3P_2$ atoms to the ground state after a time-of-flight (TOF) time. A 770 nm ($^3P_2 \leftrightarrow {}^3S_1$) resonant pulse excites atoms from the $^3P_2$ state to the $^3S_1$ state, from which all the $^3P_2$, $^3P_1$, and $^3P_0$ states are populated through spontaneous decay. By simultaneous application of a 649 nm ($^3P_0 \leftrightarrow {}^3S_1$) resonant pulse, all atoms return through the $^3P_1$ state to the ground state where we can use

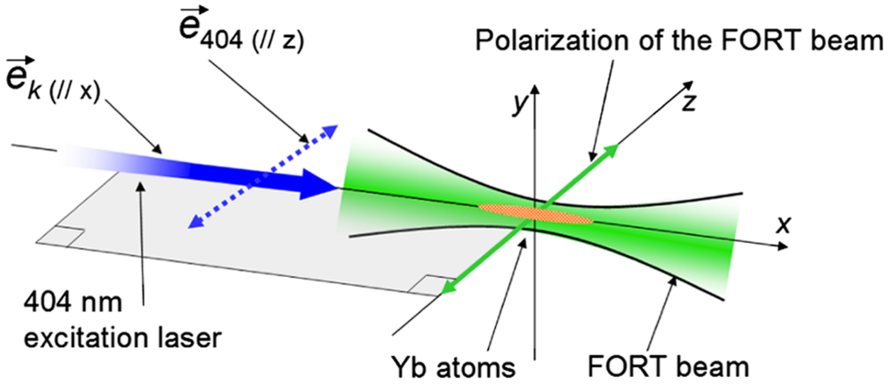

FIG. 2 (color online). Experimental setups are schematically shown. The $\vec{e}_{404}$ and $\vec{e}_k = \vec{k}/|\vec{k}|$ are the polarization and the wave number vector of the 404 nm excitation laser.

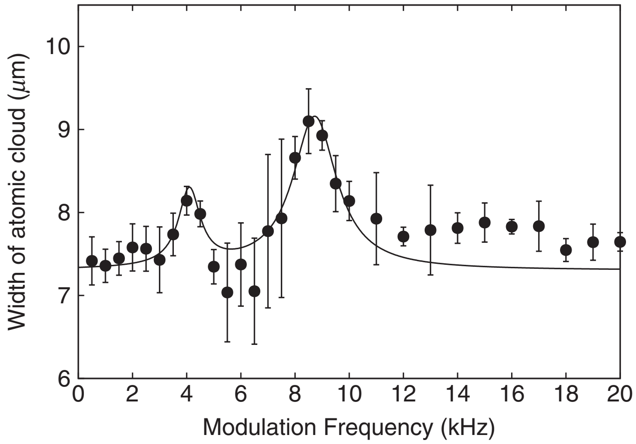

FIG. 3. Measurement of the trap frequency of the $^3P_2$ state by using the parametric resonance technique. Two resonance signals are observed at 8.6 and 4.3 kHz, respectively.

an absorption imaging technique at the stage E. Since 100 μs duration for the repumping procedure is short enough compared with a typical TOF time, we can safely regard that the observed atomic distribution precisely reflects that of atoms in the $^3P_2$ state.

To accurately determine the trap parameters as well as the atom density, we first measured a trap frequency for the atoms in the $^3P_2$ state in the single FORT by using a parametric resonance technique [24], where atoms are heated at the modulation frequency $\omega = 2\omega_{\mathrm{trap}}/n$ with ω_{trap} the trap frequency and n an integer. To this end, the FORT power was modulated at the stage C (see Fig. 1). Here we took special care about the cancellation of a magnetic field since the light shifts due to the FORT beam in the presence of a large magnetic field are quite sensitive to the relative orientation between the magnetic field and the FORT polarization [25]. We measured the number of remaining atoms and the width of the atomic cloud, which are shown in Fig. 3. Two resonance signals corresponding to $n = 1$ and 2 are clearly observed at 8.6 and 4.3 kHz, respectively, while the trap frequency of the $^1S_0$ state in this condition is 3.9 kHz. The resonance frequency is determined by fitting a Lorentzian function to the width of atomic clouds. Since all the magnetic sublevels of the $^3P_2$ state are populated in this measurement and in fact we experimentally confirmed that the atoms in every sublevel are trapped, their trap frequencies can be thought to coincide with each other within the resolution of this measurement. This result is consistent with the measurement of polarizabilities of magnetic sublevels of the $^3P_2$ state using the ultranarrow $^1S_0 \leftrightarrow {}^3P_2$ transition in our different work, which indicates that the difference of the trap frequency between magnetic sublevels is less than 1 kHz [13]. Thus, in the following discussion, we consider that the trap depth of all magnetic sublevels of the $^3P_2$ state is the same. With this information on the trap, we can accurately estimate a density.

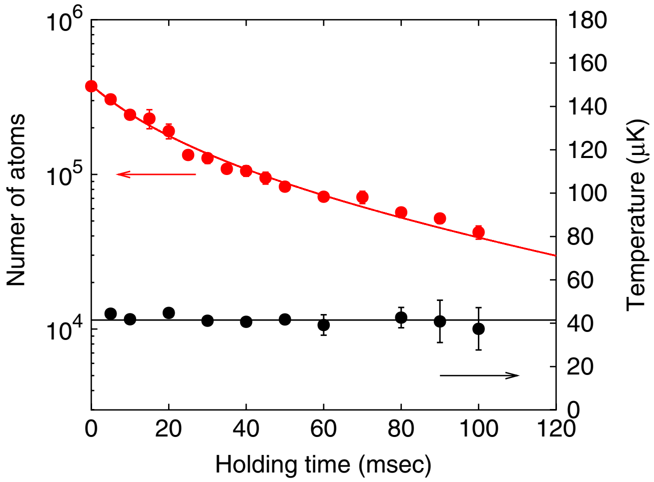

FIG. 4 (color online). Number of atoms and temperature of atoms in the FORT are plotted as a function of holding time. The nonexponential rapid decay implies the large two-body loss rate of metastable atoms. Almost constant temperature during the measured holding time indicates that the system is in the thermal equilibrium.

We successfully obtain high density ultracold metastable Yb[$^3P_2$] by exciting precooled Yb[$^1S_0$] in a FORT. These atoms are prepared at a density of 2×10^{14} cm^{-3} and at a temperature of less than 0.7 μK in a crossed FORT. In this Letter, a crossed FORT has been used only in this measurement and a single FORT has been used in all other measurements. During excitation from the ground state to the $^3P_2$ state, the atoms suffer from heating due to the spontaneous decay. As a result, the density of atoms decreases and the temperature increases, resulting in density $n = 2 \times 10^{13}$ cm^{-3}, temperature $T = 2.0$ μK and PSD $= 5 \times 10^{-3}$ for the most populated substate. This is the highest density and lowest temperature ever achieved for $^3P_2$ atoms. Although in principle PSD could be increased by direct evaporative cooling of the Yb[$^3P_2$] atoms, we found this impossible due to an inelastic collisional process which we identify as fine-structure changing collisions.

We studied inelastic loss by measuring the trap loss of Yb[$^3P_2$] atoms from a single FORT with the constant FORT intensity. Figure 4 shows the number of $^3P_2$ atoms in the FORT as a function of time after loading. Note that the (presumably state independent) one-body trap loss lifetime due to background gas collisions is measured to be 15 s, much longer than the observed trap lifetime. A significant feature of the data is the nonexponential decay of atom number along with the constant temperature of $T = 41$ μK. Our model for atom loss includes a combination of one-body loss and two-body loss, as embodied in the equation $dN/dt = -\Gamma N - \beta' N^2$, where Γ is the one-body loss rate and β' is the measured two-body atom loss rate. The solid line in Fig. 4 for data of the number of atoms in the FORT is a fit by this equation. β' is related to the density related (volume independent) two-body loss rate coefficient β by $\beta = \beta' V_{\mathrm{eff}}$, where V_{eff} is the effective volume of the atoms. In the present experiment, the volume V_{eff} can be well approximated by a cylinder with the size of the FORT beam [26] and given by $V_{\mathrm{eff}} = \pi \omega_0^2 z_R \sqrt{1/(\eta - 1)} \ln(\eta/(\eta - 1))$, where ω_0 and z_R are the beam waist and the Rayleigh length of the FORT beam, respectively. η $(= U_0/(k_B T))$ is the ratio of the trap depth U_0 to the temperature T, and k_B is the Boltzmann constant. From the measured trap frequency, the trap depth is found to be $U_0/k_B = 193$ μK for all magnetic sublevels and thus $\eta = 4.7$ which remains constant throughout the 120 ms holding time.

The two-body collisional loss of atoms from the trap can be due to elastic and inelastic processes, identified as elastic (β_{el}) and inelastic (β_{in}) collision rates, respectively. Under thermal equilibrium conditions, the relation between the observed two-body decay rate β and the elastic β_{el} and inelastic β_{in} collision rate are described by $\beta_{\mathrm{in}} = \beta/(f\gamma + 1)$, $\beta_{\mathrm{el}} = \beta\gamma/(f\gamma + 1)$, where f is the evaporation fraction and $\gamma \equiv \sigma_{\mathrm{el}}/\sigma_{\mathrm{in}}$ is the ratio of the elastic to inelastic cross sections [27]. All of these parameters f and γ are functions of only η. Thus, by slightly modifying the method in [27], we estimate both the inelastic scattering rate $\beta_{\mathrm{in}} = 1.0(3) \times 10^{-11}$ cm^3 s^{-1} and the elastic one $\beta_{\mathrm{el}} = 2.3(6) \times 10^{-11}$ cm^3 s^{-1} for the temperature 41 μK. The elastic binary collision rate can be independently investigated by the cross-dimensional relaxation measurement [28] and the result was consistent with the above estimation.

Considering the suppression of m-changing collisional loss in our FORT which can trap atoms in every magnetic sublevel of the $^3P_2$ state with zero magnetic field, the observed inelastic collision rate is anomalously large. Thus a different inelastic collision process—fine-structure changing collisions—is strongly suggested. The previous theoretical works revealed details of fine-structure changing transitions only at a high temperature [16–19]. However, there has been no theoretical work on the fine-structure changing collisions between atoms in the $^3P_2$ state at ultralow temperature achieved in the present work. As our experimental results suggest, further theoretical investigation is needed to quantitatively explain the observed inelastic collision rate. It is interesting to investigate the dependence of the loss on the dimensionality of a trap, which may lead to a possible suppression of the inelastic loss.

In conclusion we have optically trapped high density metastable ytterbium atoms in the FORT. The achieved number density is 2×10^{13} cm^{-3} at a temperature 2 μK. The nonexponential rapid loss of atoms in the FORT at a constant temperature is observed, and then a large inelastic binary collision rate constant is measured. We interpret this as fine-structure changing collisions between $^3P_2$ atoms.

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