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Quadratic collisional loss rate of a ^{7}Li trap

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We report a measurement of the quadratic collisional loss rate coefficient β of a ^{7}Li trap as a function of the trap potential in a range covering the energy of the fine-structure splitting $^2P_{3/2}$-$^2P_{1/2}$. The value of β decreases an order of magnitude when the trap potential is increased beyond 0.24 K, and reaches the minimum value of 3×10^{-13} cm^3 s^{-1} at 0.45 K. At a higher trap potential the β increases proportionally to the trap potential.

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The collisional loss rate of neutral atom traps, especially of alkali-metal-atom traps, has been intensively studied since the first demonstration of the Na laser trap [1–11]. This is partly motivated to achieve a higher atomic density, which may result in finding new many-body effects. However, the density of alkali-metal-atom traps has been found to be limited by binary inelastic collisions of trapped atoms. For Cs and Rb the loss rate increases with the laser power due to the fine-structure–state-changing collision in the upper state $^2P_{3/2}$ of the cooling transition.[8,10] The atoms acquire a sufficient kinetic energy to escape the trap, because the fine-structure splitting $^2P_{3/2}$-$^2P_{1/2}$ is much larger than the trapping potential. The quadratic collisional-loss-rate coefficient β becomes minimum at a laser power density much lower than the saturation power of the transition at which an efficient capturing of atoms is difficult. The same situation is expected for most alkali-metal atoms. The fine-structure splitting of Li, however, is only 0.48 K, and the trap potential can be made much deeper than the splitting. In this case the only remaining loss mechanism is the radiative redistribution, where the atoms gain kinetic energy by emitting a redshifted spontaneous photon during the collision. Therefore, for Li we can expect a loss-rate coefficient close to or smaller than the minimum value of Rb and Cs, which is of the order of 10^{-13} cm^3 s^{-1}. Julienne and Vigué have predicted an even smaller value [11]. In this Rapid Communication we report a quantitative measurement of the β of a ^{7}Li trap and its dependence on the trapping potential. Contrary to the case of Cs and Rb, the collisional-loss-rate coefficient of Li remained small even at a higher laser intensity. However, the absolute value was considerably larger than the prediction.

The loss rate was obtained from the decay of the fluorescence intensity from the Li trap, after the Li atomic source had been shut off. The procedure to trap Li atoms was described in a previous report [12]. The experimental setup is shown in Fig. 1. The atoms were slowed by a 671-nm laser resonant to the $^2S_{1/2}(F=2)$–$^2P_{3/2}(F=3)$ cooling transition in an intensity-varying magnetic field [13], and trapped in a magneto-optical trap with a four-beam configuration [14]. The laser was tuned 8 MHz below the slowing transition frequency. It passed through an acousto-optic modulator that modulated the laser beam with a square wave at 500 kHz. By changing the on-off ratio of the square wave the effective potential depth of the trap was controlled. The laser beam then passed through an electro-optic modulator to produce sidebands at $\pm$820 MHz. The upper sideband was resonant to the $^2S_{1/2}(F=1)$–$^2P_{3/2}(F=2)$ transition, and was used to optically pump the $F=1$ population back to the cooling transition. The $1/e^2$ beam diameter at the trap was 18 mm. The power density of each laser beam at the frequencies of the cooling transition and of the optical pumping were 7.5 mW/cm^2 and 2.5 mW/cm^2, respectively. The magnetic field gradient of the trap along the symmetry axis was 34 G/cm. The fluorescence intensity from the trap was measured by a *p-i-n* photodiode (Hamamatsu S1723-04). A charge-coupled-device (CCD) camera recorded the spatial pattern of the trapped atoms.

The trapping laser beams were carefully aligned to produce a small stable cloud of atoms at the center of the trap. Its $1/e$ diameter was approximately 500 μm, and the maximum density of atoms was 10^{11} cm^{-3}. The small diameter ensured that the cloud diameter remained

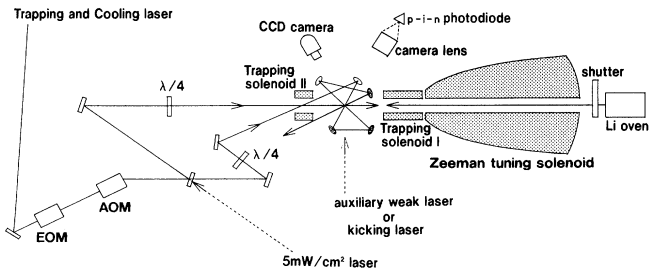

FIG. 1. Optical configuration of the decay rate measurement. EOM and AOM stand for electro-optic modulator and acousto-optic modulator, respectively.

constant within 10% during the decay measurement.

The measured decay of the fluorescence intensity I was fitted with the equation

$$\frac{dI}{dt} = -\beta(I - I_0)^2 - \alpha(I - I_0) , \quad (1)$$

where I_0 was a constant arising from the scattered light and the offset of the amplifier, and α the linear loss due to collisions with residual gas molecules. Figure 2 shows a typical decay curve and the fitting with Eq. (1). To obtain the absolute value of β, we need to know the absolute atomic density of the trap. First, the number of trapped atoms in the $^2P_{3/2}$ state was determined by multiplying the fluorescence flux quanta from the trap by the natural lifetime of 27 ns [15]. The absolute fluorescence intensity was obtained from the photocurrent of the p-i-n photodiode using the measured transmission of the collecting lens system and the company-supplied value of the quantum efficiency of the photodiode, which was 70%. To find the total number of the trapped atoms we determined the population ratio of the trapped atoms using the linear absorption. An auxiliary weak laser beam was sent through the trap to measure the linear absorption spectrum of the D_1 transition, $^2S_{1/2}$-$^2P_{1/2}$. The trapping laser was turned off for 20 μs at an interval of 1 ms, while scanning the auxiliary laser slowly through the absorption lines. The laser power was kept sufficiently low to avoid optical pumping. The absorption coefficient increased while the trapping laser was off, reflecting the increase of the ground-state population. From the absorption coefficients of two ground-state hyperfine transitions with and without the trapping laser, we calculated the population ratio among the $^2S_{1/2}(F=1)$, $^2S_{1/2}(F=2)$, and the sum of all hyperfine levels of the $^2P_{3/2}$. They were 31%, 44%, and 25% for $^2S_{1/2}(F=1)$, $^2S_{1/2}(F=2)$, and $^2P_{3/2}$, respectively. Finally, the density of the trapped atoms was determined from the number of trapped atoms divided by the volume of the atomic cloud that was measured using the CCD camera.

Figure 3 shows the quadratic collisional-loss-rate coefficient β as a function of the duty ratio of the trapping laser. The overall accuracy of the absolute value is approximately 35%. The largest error arises from the uncertainty of the trapped-atom density. The result is markedly different from the case of other alkali atoms, Cs [8] and Rb [10]. The β is approximately 3×10^{-12} cm^{3}s^{-1}, when the duty ratio is small. It decreases by an order of magnitude when the duty ratio is increased from 40% to 60%, and shows a minimum value of 3.2×10^{-13} cm^{3}s^{-1} approximately at 70%. Those characteristics are qualitatively similar to those of Cs and Rb. However, the laser power at the minimum value is much higher than the case of Cs and Rb. In addition, the β increases proportionally to the duty ratio above the 70% point, as is seen in Fig. 3(b). This behavior is consistent with the loss mechanism of a Li trap. If the trap potential is deeper than one-half of the fine-structure splitting $^2P_{1/2}$-$^2P_{3/2}$, the only loss mechanism is binary collisions with the radiative redistribution. Therefore, the β should remain small at high laser power, and increase suddenly when the trap potential is reduced below one-half of the fine-structure splitting.

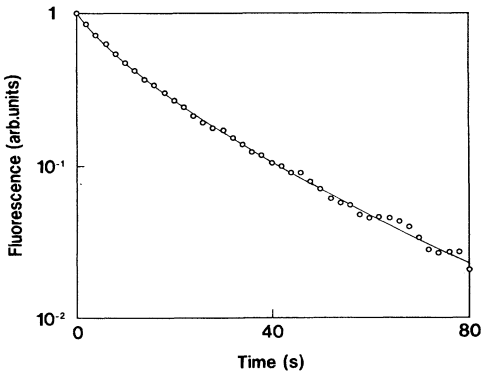

FIG. 2. Fluorescence decay from trapped atoms as a function of the time after stopping the loading of atoms: the open circle shows the experimental decay and the solid line the fitting with Eq. (1). The scale of 1 in the ordinate is roughly 10^{11} cm^{-3}.

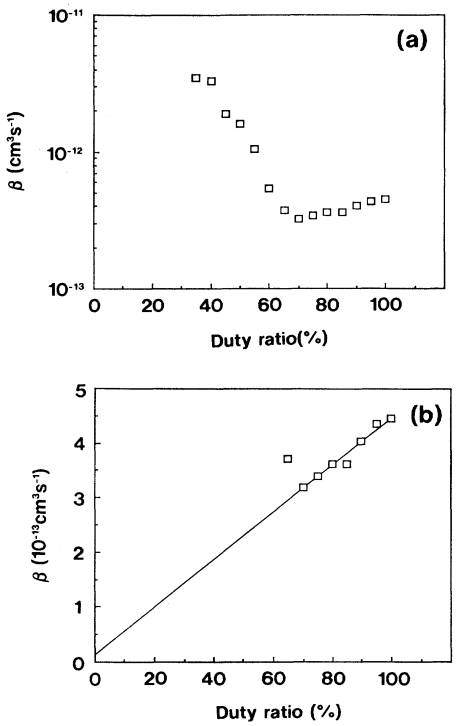

FIG. 3. Collisional-loss-rate coefficient β vs duty ratio of the trapping laser: (a) logarithmic scale, (b) vertically expanded view with linear scale.

We measured the effective trap potential with the kick-and-recapture method used by Raab *et al.* [16]. The kicking laser was sent either from the axial direction along the slowing laser, or from the radial direction. The measured potential depth was 0.64 K along the radial direction and 1.3 K along the axial direction at the duty ratio of 100%. Therefore, the trap potential of 0.48 K/2 corresponds to the 40% duty ratio point of Fig. 3, where the value of β starts to decrease towards higher potential. In a magneto-optical trap the effective trap potential may be proportional to the square root of the duration of the

trapping laser rather than the linear dependence [10]. In this case the transition should occur at around 60%, which is in the bottom of the slope. Our result is qualitatively in agreement with the assumption of the fine-structure changing collision, but is not sufficient to distinguish the two cases.

Although the potential dependence of the β is in agreement with the prediction, the minimum value of 3.2×10^{-13} cm^2 s^{-1} is much higher than the value predicted by Julliene and Vigué [11]. In order to strengthen our confidence in the fact that the observed β at high duty ratio is due to the redistribution collision, we performed an additional experiment. It has been known that the illumination of a laser with a frequency at the lower side of the resonance increases the loss rate, due to the increase of the redistributional collision [8,9]. Since we use an electro-optic modulator to obtain a higher-frequency sideband for the hyperfine pumping, there is always a lower sideband 820 MHz below the resonance. To estimate the effect, we superposed a 5-mW/cm^2 laser on the trapping beams and scanned its frequency through the resonance of the cooling transition. The fluorescence intensity from the trapped atoms was found to decrease when the frequency of the scanning laser was tuned in the range between -200 and -600 MHz. However, no influence was observed at -800 MHz. Therefore, we can conclude that the observed value of β was not affected by the existence of the lower sideband.

In conclusion, we measured the laser power dependence of the quadratic collisional-loss-rate coefficient of ^{7}Li. At higher trapping laser intensity, the loss is caused solely by redistribution collisions and remains small, which is contrary to the case of other alkali-metal atoms. The rate coefficient due to the radiative redistribution was also determined from the absolute value of β. Our result shows that it is possible to obtain higher density compared with other alkali-metal atoms. However, the minimum value is not so much different from that of Rb.

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