Collisional Losses from a Light-Force Atom Trap

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We have studied the collisional loss rates for very cold cesium atoms held in a spontaneous-force optical trap. In contrast with previous work, we find that collisions involving excitation by the trapping light fields are the dominant loss mechanism. We also find that hyperfine-changing collisions between atoms in the ground state can be significant under some circumstances.

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Spontaneous-force light traps[1,2] have provided a way to obtain relatively deep static traps for neutral atoms. These allow one to produce samples containing large numbers of very cold atoms. In this paper we present an experimental study of the collisions which eject atoms from such a trap. These collisions are of considerable interest because the temperatures of the trapped atoms (10^{-4} K) are far lower than in usual atomic collision experiments. The theory of such low-energy collisions and their novel features have been discussed by several authors.[3-7] Perhaps the most notable feature is that the collision times are very long, and the collision dynamics are dominated by long-range interactions and spontaneous emission. These collisions also have important implications with regard to potential uses of optically trapped atoms. For many applications the maximum density that can be obtained is a critical parameter, and these collisions limit the attainable density.

There have been two experimental studies of collisions in optical traps. Gould *et al.*[8] measured the cross section for associative ionization of sodium. However, there is no evidence that this process is significant in limiting trapped-atom densities, and for some atoms, including cesium, it is energetically forbidden. Prentiss *et al.*[9] studied the collisional losses which limited the density of sodium atoms which were held in a spontaneous-force trap. Their surprising and unexplained results were a direct stimulus for our work. In particular, they observed no dependence of the loss rate on the intensity of the trapping light. This was quite surprising, because a ground and an excited atom interact at long range via the strong $1/r^3$ resonant dipole interaction, and a portion of the excited-state energy can be converted into sufficient kinetic energy to allow the atoms to escape from the trap. By comparison, two atoms in their ground states interact only through a much weaker short-range $1/r^6$ Van der Waals attraction, and even when such collisions occur, they may not produce significant kinetic energy to cause trap loss. This implies that the dominant collisional loss mechanism would involve the excited atomic states, and thus depend on the intensity of the light which causes such excitations.

In this paper we present measurements which show that, in contrast with Ref. 9, the collisional loss rate has a marked dependence on the trap laser intensity. We will present strong circumstantial evidence that the dependence at very low intensities is due to hyperfine-changing collisions between ground-state atoms. We believe that the loss rates at higher intensities are associated with collisions involving excited states, and are the type discussed by Gallagher and Pritchard.[7]

As discussed in Ref. 7, these collisions are very different from normal ground–excited-state atomic collisions in which two initially distant atoms, A and A^*, approach, collide, and separate in a time much less than the radiative lifetime of the excited state. In contrast, for these very-low-temperature collisions the absorption and emission of radiation in the midst of the collision drastically alter the motion. In particular, if the excitation takes place when the two atoms are far apart ($R > 1000$ Å) they will reradiate before being pulled into the small-R region where energy transfer occurs. However, if they are sufficiently close when excited, they can be pulled close enough together for substantial potential energy to be transferred into kinetic energy before decaying. The two dominant transfer processes are excited-state fine-structure changes and radiative redistribution. In the first, A^* changes its fine-structure state in the collision and the pair acquire a fine-structure-interval worth of kinetic energy. The second process, radiative redistribution, refers to A-A^* reemitting a photon which, because of the A-A^* attractive potential, has substantially less energy than that of the photon which was initially absorbed. This energy difference is transferred to the subsequent kinetic energy of the ground-state atoms. The trap loss rate depends on the probability of exciting such "close" A-A^* pairs, and this probability is determined by the frequency and intensity of the exciting radiation. Light which is tuned to the red of the atomic resonance frequency, ν_0, excites pairs which are closer together (and shifted in energy) and thus is more effective at causing trap loss than light which is at ν_0.

We tested this hypothesis by examining how the loss

rate changes when the trapped atoms are illuminated by an additional laser tuned far from resonance. It is particularly straightforward to interpret this second measurement because such a red-detuned "catalysis" laser is very ineffective at exciting isolated atoms and, hence, has a negligible effect on the trap depth. Also, as discussed below, it is considerably simpler to theoretically predict the collisional loss rate for the case of large detuning.

Much of the apparatus for this experiment was the same as in our earlier work with cesium in optical molasses, and the arrangement of laser and atomic beams is very similar to that discussed in Ref. 10. A beam of cesium atoms effused from an oven and passed down a 1-m tube into a UHV chamber (10^{-10} Torr). In this chamber the atoms were trapped using a Zeeman-shift spontaneous-force trap[2] formed by having three perpendicular laser beams which were reflected back on themselves. The beams were all circularly polarized, with the polarizations of the reflected and incident beams being opposite. They had Gaussian profiles with diameters of about 0.5 cm, and were tuned to the $6S_{F=4}$ to $6P_{3/2\,F=5}$ transition of cesium. Magnetic field coils which were 3 cm in diameter and arranged in an anti-Helmholtz configuration provided a field which was zero at the middle of the intersection of the six beams, and had a longitudinal gradient of 5.1 G/cm. In addition to the main trap laser beams, there were beams to ensure the depletion of the $F=3$ hyperfine ground state in the trap. Thus all the trapped atoms were in the $F=4$ ground state. Two other lasers, the "catalysis" and "stopping and probing" lasers, were used on occasion as discussed below. All the lasers were diode lasers whose output frequencies were controlled by optical and electronic feedback and had short-term linewidths and long-term stabilities of well under 1 MHz.

The fluorescence from the trapped atoms was observed with both a photodiode, which monitored the total fluorescence, and a charged-coupled-device television camera which showed the size and shape of the atomic cloud. The spatial resolution was about 10 μm. Data acquisition involved the following sequence: First, atoms were loaded into the trap by opening a flag which blocked the cesium beam. When the trap laser intensity was very low the stopping laser was used to slow the atoms for loading as in Ref. 10. After a few seconds the cesium and stopping laser beams were again blocked, the video image of the trap was digitized and stored, and the total fluorescence signal was measured as a function of time for the next 205 s. In a separate measurement, we determined the density and the excited-state fraction by loading the trap under the same conditions and observing the absorption of a weak probe beam by the cloud with the trapping light on, and 1 ms after it had been switched off. To measure the temperature of the trapped atoms the probe was moved a few mm to the side of the cloud and the time-of-flight spectrum was observed after the trap light was turned off, as in Ref. 11. The temperature was found to be between 2.5 and 4×10^{-4} K.

In the initial stages of this work we loaded the trap with as many atoms as possible. This produced a large low-density cloud of trapped atoms which had a loss rate which was proportional to the total number of trapped atoms. The behavior of the cloud in this large-number regime showed a variety of complex cooperative behaviors which will be discussed in a later publication. We subsequently discovered that, when the number of atoms in the trap decreased, the diameter of the cloud diminished, while the density increased. When the number was much lower, the cloud became a small Gaussian sphere with a diameter of about 1.7×10^{-2} cm. Further reduction in the number of atoms then only reduced the density but not the diameter.

In Fig. 1 we show the fluorescence signal from the cloud in this constant-diameter regime, along with a fit which assumes a loss rate of the form $dn/dt=-\alpha n-\beta n^2$, where n is the density of atoms in the trap. We also assume that the fluorescence is proportional to the density. The figure shows that this is the appropriate dependence, and the n dependence indicates that collisions between the trapped atoms are causing loss from the trap. The α term is responsible for a simple exponential decay. For all the data presented here, we were careful to ensure that the initial number of atoms in the trap (3×10^4) was low enough that the cloud diameter remained constant. This was verified both by directly measuring the cloud diameter and by checking that the fluorescence decay had the expected time dependence.

As mentioned earlier, we measured collisional losses under two different conditions. The first approach, similar to that used in Ref. 9, was to simply examine the rate at which atoms were lost from the trap as a function of

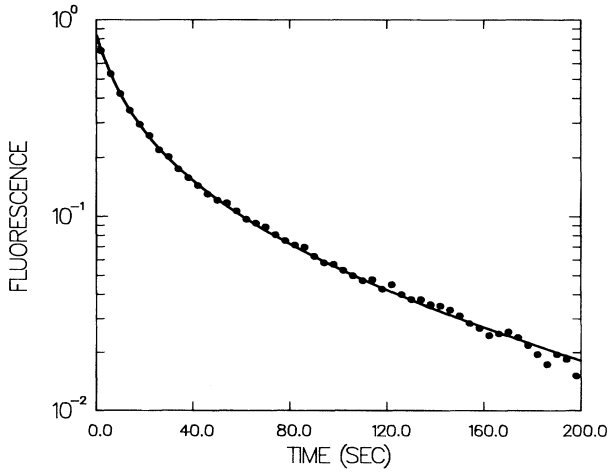

FIG. 1. Fluorescence from the cloud of trapped atoms as function of time after the loading is terminated. The solid line is a fit to the data taking the loss rate to be $\alpha n+\beta n^2$, where the initial density was $1.2\times10^9/\text{cm}^3$, giving $\alpha=1/(132$ s), and $\beta=7.6\times10^{-11}$ cm^3/s.

the intensity of the trap laser light. The quantity of interest was the coefficient β, since α depends only on the background pressure in the vacuum chamber. To find β, we fitted the fluorescence decay curves as in Fig. 1 to get βn_0, and from the absorption measurements and the video image we obtained the initial density, n_0. The digitized image of the cloud showed that the fluorescence was a Gaussian distribution as one would expect. The initial density was between 1 and 4×10^9 atoms/cm^3, and the probe-beam absorption was 2.5% to 10%. In Fig. 2 we show the dependence of β on the total intensity of all trap laser beams for a trap laser detuning of 5 MHz (1 natural linewidth). The scatter in the points provides a reasonable estimate of the uncertainty in the measurements. We should mention that there was far more scatter in the data before considerable effort was expended to improve the quality of the laser beam wave fronts, the alignment, and the measurement of the trap size.

We interpret the data as follows. The large β values seen in Fig. 2 for intensities less than 4 mW/cm^2 are due to hyperfine-changing collisions between ground-state atoms. Two atoms acquire velocities of 5 m/s if they collide and one changes from the $6S_{F=4}$ hyperfine state to the lower $F=3$ state. For high trap laser intensities, atoms with this velocity cannot escape, but at lower intensities the trap is too weak to hold them. We also find that if the beams are misaligned slightly, a similarly large-β loss rate is observed for all intensities. We estimate that hyperfine-changing collisions between ground-state atoms due to the Van de Waals interaction will give a β in the range 10^{-10} to 10^{-11} cm^3/s, which is consistent with the data shown in Fig. 2. Above 4 mW/cm^2, β appears to increase linearly with intensity. We believe that this is due to the energy-transfer collisions of the type discussed above.

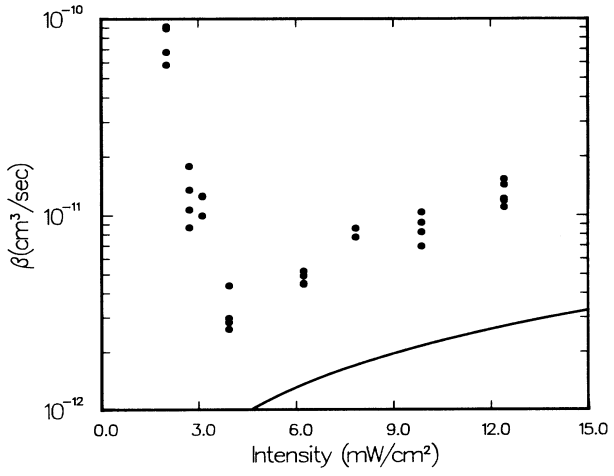

FIG. 2. Dependence of β on the total intensity in all the trap laser beams. The solid line indicates the prediction of the Gallagher-Pritchard model, and would be a straight line if the scale were linear.

We studied these collisions in more detail by using an additional laser to illuminate the atoms in the trap. As mentioned earlier, measuring the β caused by this laser when it is detuned to the red provides a particularly good way to test the Gallagher-Pritchard model for these collisions. The data acquisition in this case was exactly the same as before. In Fig. 3 we show the results. These data were taken with a trap laser intensity of 13 mW/cm^2 and a detuning of 5 MHz. The solid line is the prediction obtained using the Gallagher and Pritchard model.[12] For detuning greater than 100 MHz the curve turns over simply because of the decrease in the number of pairs with such small separations. (A frequency shift of 100 MHz corresponds to a separation of about 500 Å.) The agreement between theory and experiment is excellent in view of the estimates used in the calculation, which are discussed below, and the experimental uncertainties.

It is much less straightforward to compare the results shown in Fig. 2 with theory because the laser detuning is much smaller. The calculation in Ref. 7 neglects the excited-state hyperfine splitting and the initial atomic velocity which are substantially more important effects in the small-detuning case. When the laser is tuned close to the atomic resonance, the initial interatomic force is weak because the colliding atoms are relatively far apart. As a result, the probability of the atom getting in to small R before radiating has some dependence on its initial velocity. This probability also depends very sensi-

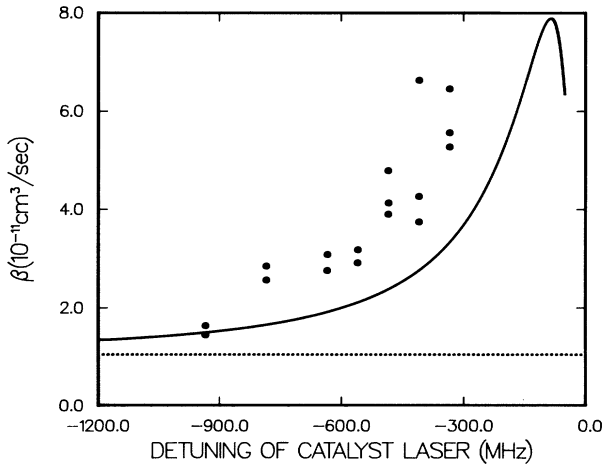

FIG. 3. Dependence of β on detuning of the catalysis laser. The zero of detuning corresponds to the center of gravity of the $6P_{3/2}$ hyperfine states. The absence of data for a detuning of less than 300 MHz is caused by the need to be well away from all $6S$-to-$6P_{3/2}$ hyperfine transitions to avoid perturbing the trap. These data are for a catalysis laser intensity of 24 mW/cm^2. The dotted line shows the value of β which is obtained when the catalysis laser is not present. The solid line indicates the predictions obtained using the Gallagher-Pritchard model.

tively on the shape of the potential, which, at these distances, will be strongly affected by the excited-state hyperfine interaction and clearly will not be the simple C_3/R^3 dependence which was assumed. This could easily change the potential enough to shift the theoretical result by a factor of 5, and hence would explain the difference between the magnitudes of the theoretical and experimental results. The theory does predict that β should increase linearly with intensity which is what we observe. For the larger detunings used with the catalysis laser, the theory is less sensitive to the shape of the potential curves and the atomic velocity, because the probability of reaching small R is approaching 1. However, a factor of 2 error is still not surprising.

It is not clear why our results differ from those of Prentiss *et al.*, but we do not think it is likely that sodium behaves fundamentally differently from cesium. One possibility is that for the range of intensities they used the sum of hyperfine-changing and excited-state collisional losses remained roughly constant.

We have shown that collisions which depend on the trap laser intensity will be an important factor in determining the densities attainable in optical traps. This will be true of all types of optical traps, but the exact loss rate will depend on the frequency and intensity of the laser light present. Also, ground-state hyperfine-changing collisions can be an important loss mechanism if the trapped atoms are not in the lowest hyperfine state and the trap is not sufficiently deep.

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