Excited-State Collisions of Trapped ^{85}Rb Atoms

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We describe a new method for measuring excited-state collisions between optically trapped atoms. With this method, trap-loss collision rates are deduced from the loading behavior of clouds of trapped atoms in the regime where radiation trapping limits the atom density. Our measurements indicate that ^{85}Rb trap-loss collisions occur at significantly smaller rates than expected both from previous work on Cs and from recent models. In addition, the dependence of the trap-loss collisions on the frequency of the light used to excite the atom pairs is also different from that of Cs, suggesting that assumptions about the dynamics in these models need modification.

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Laser techniques for trapping and cooling neutral atoms produce samples with densities approaching 10^{11} cm^{-3} at temperatures of 1 μK to 1 mK. Under these conditions, collisions between the trapped atoms have been observed in several experiments [1–5]. Since the collisions occur at low temperature and over long durations, they are uniquely sensitive both to long-range interatomic forces and to the absorption and emission of radiation during the collisions. The most readily observed manifestation of these collisions is loss of atoms from the trap due to the collisions.

We report a new technique for measuring trap-loss collision rates, and present the first measurements of excited-state collisions of trapped ^{85}Rb atoms. The observed rates are about a factor of 5 smaller than predicted by recent models [6,7] of the collisional dynamics and energy transfer process. We also measure the dependence of the collision rates on the frequency of the light used to excite the atom pairs. The qualitative shape of the frequency dependence is similar to previous measurements of Cs trap-loss rates [3,4], but, contrary to expectation, peaks nearer to the atomic resonance. Since the shape of the frequency dependence is primarily sensitive to the dynamics of the collisions at large interatomic separations (as opposed to the energy transfer processes which take place at small interatomic separations and therefore only affect the magnitude of the collision rates in a detuning-independent manner), we believe that new models of the collisional dynamics will be required to explain the observed collision rates.

Our measurement technique exploits the radiation trapping properties of optically thick clouds of trapped atoms. Recent studies have shown that radiation trapping limits the density of such clouds of trapped atoms [8,9]. As atoms are added to or removed from the cloud, the density of the cloud stays approximately the same but the volume increases or decreases. Since the density stays the same, the collision rates also remain fixed. This assumes that temperature changes [9] do not affect the collision rates as has been argued previously [6,7]. Also, this assumes that radiation trapping only affects the collisions indirectly by modifying the density distribution. With these assumptions we see that it is not necessary to use small numbers of atoms to investigate trap-loss collisions; we can use samples with large numbers of atoms in simple cell traps [10] rather than the more complicated atomic-beam-based traps used previously [1–5].

The optical trap used for this experiment is of the Zeeman-tuned type [11], loaded directly from slow ^{85}Rb atoms present in room-temperature Rb vapor [10]. Two diode lasers whose frequencies are controlled by optical feedback from Littrow-mounted gratings [12] are used for trapping the atoms: the "trapping" laser (1.5 cm diameter, arithmetic sum of the individual beam intensities 5.0 ± 0.5 mW/cm^2) was tuned 6.9 ± 0.5 MHz below the ^{85}Rb $5S_{1/2}(F=3)$-$5P_{3/2}(F'=4)$ transition, and the "hyperfine pumping" laser (1.5 cm diameter, 1.8 mW/cm^2) was tuned near the $5S_{1/2}(F=2)$-$5P_{3/2}(F'=3)$ transition. The trapping laser provides radiation pressure for stopping, cooling, and trapping of the atoms, while the hyperfine pumping laser is responsible for countering optical pumping into the $5S_{1/2}(F=2)$ state. The total pressure in the ion-pumped stainless-steel vacuum chamber was about 1×10^{-9} torr while the Rb vapor pressure was kept less than 10^{-10} torr by isolating the Rb reservoir from the chamber with a valve. This minimized the loss of atoms from the trap due to collisions with hot Rb atoms. Using an absorption technique in conjunction with density distribution measurements obtained with a charge-coupled-device camera, we measured a trapped-atom density of typically $(2.8\pm0.4)\times10^{10}$ cm^{-3}. This absorption measurement was used to calibrate fluorescence detection of the number of trapped atoms.

The trap is loaded continuously at a rate L (atoms/s) from the low-velocity tail of the Maxwellian velocity distribution for the room-temperature Rb atoms. Two types of loss processes occur: collisions with room-temperature background atoms which occur at a rate γ per trapped atom (proportional to the pressures of both Rb and vacuum residuals), and collisions between trapped atoms that transfer sufficient kinetic energy to eject the atoms from the trap. The loss rate due to trapped atom collisions at each position in the trap is $\beta n^2(\mathbf{r},t)$, where β is the rate coefficient for the trap-loss collisions between trapped atoms, and $n(\mathbf{r},t)$ is the density distribution of the trapped atoms. Thus the rate equation that governs the total number N of trapped atoms as a function of time t is

$$\frac{dN}{dt}=L-\gamma N-\beta\int n^2(\mathbf{r},t)d^3r\,. \quad (1)$$

The density distribution is simple in two limits, either when radiation trapping is negligible [3] or when it is sufficiently strong to be the dominating factor in determining $n(\mathbf{r},t)$. As shown by Walker, Sesko, and Wieman [8], the density of the trapped atoms in the radiation trapping limit is closely approximated by $n(\mathbf{r},t)=n_c$, where n_c is a constant characteristic of the trapping conditions. Thus in the radiation trapping limit, Eq. (1) simplifies to

$$\frac{dN}{dT}=L-(\gamma+\beta n_c)N\,. \quad (2)$$

In general, at nonzero temperatures the density is reduced at the edge of the cloud, and from our density distribution measurements we have accounted for this effect. The total collision rate $\gamma+\beta n_c$ was determined by beginning with an empty trap, then turning on the trap, measuring the number of atoms in the trap as a function of time, and fitting by the simple exponential of Eq. (2). Examples of these transients are shown in Fig. 1. One might expect the transients to depart from exponentials when the number of atoms is small enough that the constant density approximation is not valid. However, this has only a minor effect on the transients; when the number is small the approximate solution to Eq. (2) is $N(t)=Lt$, independent of the collision rates. Thus over a wide range of parameters we find the assumptions leading from Eq. (1) to Eq. (2) to be valid.

In principle, γ and βn_c can be separated by varying n_c. For the case of collisions involving excited states, however, more information can be obtained by illuminating the cloud of trapped atoms with the light from a "catalysis" laser [3] to increase the collisional loss rate without affecting the operation of the trap. The intensity and detuning of the catalysis laser are chosen to have a negligible force on the atoms, but a strong effect on the collisions. Since the properties (detuning, intensity) of the catalysis laser can be varied over a wide range, much additional information is available. This technique also has the advantage that the density and temperature of the trapped atoms are not changed as the detuning and intensity of the catalysis laser are varied. The catalysis laser contribution to the collision rate is determined by subtracting the total loss rate with and without the catalysis laser entering the trap. As a systematic check, we found the loading rate L to be independent of the presence of the catalysis laser to better than $\pm 10\%$. In addition, no noticeable change in the density distribution of the atoms occurred with the catalysis laser in the trap.

In Fig. 2 we present measurements of β as a function of the detuning and intensity of such a catalysis laser. The laser was another stabilized diode laser with a beam diameter of 3.0 mm whose detuning was determined to ± 10 MHz using a saturated absorption spectrometer and a Fabry-Pérot spectrum analyzer. Detunings within six natural linewidths (± 35 MHz) of the hyperfine resonances were not used to avoid noncollisional effects of the

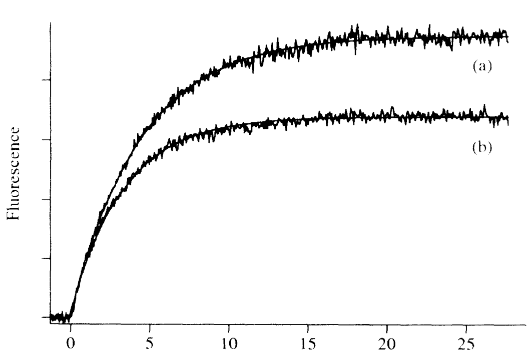

FIG. 1. Fluorescence transients observed in the loading of the trap, and fits by Eq. (2). (a) No catalysis laser. (b) Catalysis laser tuned -300 MHz from the ^{85}Rb $5S(F=3)$-$5P_{3/2}(F'=4)$ transition.

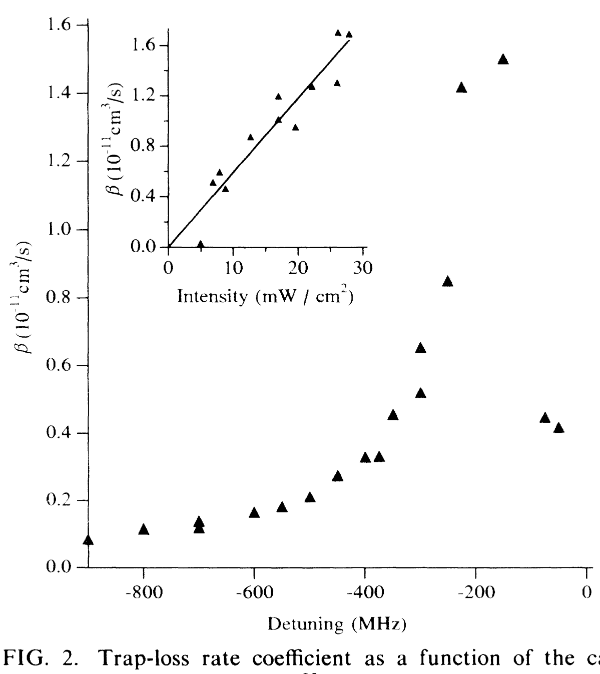

FIG. 2. Trap-loss rate coefficient as a function of the catalysis laser detuning from the ^{85}Rb $5S_{1/2}(F=3)$-$5P_{3/2}(F'=4)$ transition. The data have been scaled to correspond to a catalysis laser intensity of 10 mW/cm^2. Inset: The rate coefficient as a function of the catalysis laser intensity at a detuning of -300 MHz. The linear dependence implies a singly-excited-state collision mechanism.

catalysis laser on the trapped atoms. Since the density distribution was the most difficult parameter to measure in this experiment, we found that the most reliable method to measure β was to change the detuning of the catalysis laser, then adjust the intensity of the catalysis laser such that the total number of trapped atoms was fixed. This minimized relative uncertainties due to changes in the density distribution as the number of atoms was varied. The uncertainty in the data of Fig. 2 is estimated at 25%, dominated by the uncertainty in the density measurement. The inset of Fig. 2 shows that the intensity dependence (taken at -300 MHz detuning) of the trap-loss rate is very nearly linear, implying no saturation effects. The data are scaled therefore to correspond to a uniform catalysis laser intensity of 10 ± 1 mW/cm^2.

The shape of the detuning dependence in Fig. 2 is qualitatively similar to recent trap-loss measurements for Cs [3], duplicated in Fig. 3. The simplest model of such collisions [6,7] suggests that two major effects dominate the detuning dependence. For small detunings, the atom pairs are resonant at large interatomic distances, so the rate is small due to the interruption of collisions by spontaneous emission. At large negative detunings, the decreasing collision rate with increasing negative detuning results from having fewer atoms at small interatomic separations, where the atom pairs are resonant with the catalysis laser. This model is in excellent quantitative agreement with the Cs measurements [7]. The predictions for Rb [7] include slightly higher trap-loss rates due to the greater probability of fine-structure changes, but similar detuning dependence.

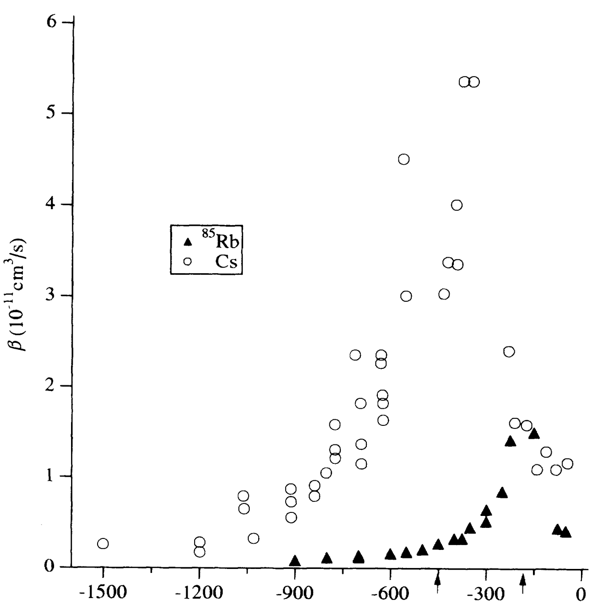

FIG. 3. Trap-loss rate coefficients for Cs and ^{85}Rb. According to current models, the ^{85}Rb rate coefficients should be slightly larger than for Cs and have a similar dependence on frequency. The observed difference in the frequency dependence suggests that current models of the collision dynamics need to be modified. The arrows on the abscissa indicate the position of the detunings that correspond to the Cs $6S_{1/2}(F=4)$-$6P_{3/2}(F'=3)$ transition at -452 MHz and the ^{85}Rb $5S_{1/2}(F=3)$-$5P_{3/2}(F'=2)$ at -184 MHz.

The ^{85}Rb measurements we report in this Letter diverge from the predictions of the models in several ways. This can be seen in Fig. 3, which shows both ^{85}Rb and Cs data. First, the trap-loss rates for ^{85}Rb are significantly smaller than for Cs. Second, the detuning dependence is peaked at much smaller detunings for ^{85}Rb than for Cs. Finally, if we extrapolate the ^{85}Rb data to small detunings, for which the models predict $\beta=(1.7\text{–}3.0)\times10^{-11}$ cm^3/s at 10 mW/cm^2, we find an experimental value of $(3.6\pm1.5)\times10^{-12}$ cm^3/s, a factor of 5 smaller than expected.

The above discrepancies between our experiments and the models suggest that the treatments of the collisions dynamics at large interatomic separations need to be modified. This follows from the observation that the absorption and emission of light occurs at large interatomic separations, whereas the collisional energy transfer process takes place at small interatomic separations, after the atoms have been already accelerated to relatively high kinetic energies of 0.1 K or more [6]. Thus we expect the dependence of the rate coefficients on detuning and intensity to arise from the dynamics of the collisions at large interatomic separations, while the energy transfer probability contributes only an overall scale factor. Thus the differing detuning dependences of the ^{85}Rb and Cs trap-loss rates imply that the dynamics of the collisions are different from those treated by the models. Since the magnitude of the rate coefficient depends both on the dynamics as well as on the energy transfer probabilities, the data do not indicate whether the calculations of the energy transfer processes need to be modified as well.

The detuning dependences of Fig. 3 peak near the detunings corresponding to the $F=3$-$F'=2$ transition in ^{85}Rb and to the $F=4$-$F'=3$ transition in Cs. This suggests that the excited-state hyperfine structure, which has been left out of the models, is important for understanding the dynamics of these collisions. Also in support of this is the recent report of Wallace *et al.* [13] that at small detunings the trap-loss rates for ^{87}Rb are a factor of 4 smaller than for ^{85}Rb.

We have demonstrated that trap-loss oscillations can be measured in clouds of atoms where radiation trapping plays a role in determining the atomic density distribution. We have studied the trap-loss rate coefficient as a function of the detuning and intensity of a catalysis laser, and find significant disagreements with recent models of these collisions. The data suggest that current models of the dynamics will need to be modified.

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