Ultracold ^{87}Rb Ground-State Hyperfine-Changing Collisions in the Presence and Absence of Laser Light

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We have measured the rate of hyperfine-changing collisions between ground-state ^{87}Rb atoms in a magneto-optical trap. Using a population switching technique, we directly measure the rate of these collisions in both the presence and absence of near-resonant trap laser light. We see a dramatic enhancement of the collision rate by the light and observe that in the absence of the light, the rate increases with increasing temperature. There is consistency between this latter measured rate at temperatures below $\sim 100\ \mu$K and theoretical calculations constrained by other recent experiments.

34.50.Rk, 32.80.Pj

The ability to produce ultracold atoms has led to the study of atomic collisions at very low temperatures (e.g., < 1 mK) [1]. These studies have led to tighter constraints on atom-atom interaction potentials and have validated the theoretical models used for ultracold collision calculations. Ultracold collisions are critically important in many of the applications of laser cooling, such as atomic fountain clocks and Bose-Einstein condensation (BEC). Since most of these applications involve ground-state atoms, there is particular interest in ground-state collisions, both elastic and inelastic. Elastic collisions at low energy are characterized by the s-wave scattering length, which determines the efficiency of evaporative cooling and many properties of BECs. Inelastic The ability to produce ultracold atoms has led to the study of atomic collisions at very low temperatures (e.g., < 1 mK) [1]. These studies have led to tighter constraints on atom-atom interaction potentials and have validated the theoretical models used for ultracold collision calculations. Ultracold collisions are critically important in many of the applications of laser cooling, such as atomic fountain clocks and Bose-Einstein condensation (BEC). Since most of these applications involve ground-state atoms, there is particular interest in ground-state collisions, both elastic and inelastic. Elastic collisions at low energy are characterized by the s-wave scattering length, which determines the efficiency of evaporative cooling and many properties of BECs. Inelastic collisions can cause loss of atoms and/or heating in ultracold samples at high density and in BECs.

We report here the results of an experiment in which we both observe and eliminate the dramatic effects of near-resonant laser light on hyperfine-changing (ΔF) collisions between ^{87}Rb ground-state atoms. In a magneto-optical trap (MOT) [2], atoms are usually maintained in the upper hyperfine level ($F = 2$ for ^{87}Rb) of the ground state. ΔF collisions cause a transfer of one (denoted $1 \times \Delta F$) or both ($2 \times \Delta F$) atoms to the lower F level, accompanied by an increase in the center-of-mass kinetic energy of the atoms. For a MOT operated at low laser intensity and/or large detuning, this energy can be sufficient to cause escape from the trap. Although ΔF collisions in our MOT occur at nearly zero magnetic field ($B < 10^{-5}$ T), they are essentially identical to the spin-exchange collisions which can occur in magnetic traps.

Ultracold ΔF collision rates have been measured and observed for Na [3,4], K [5], Rb [6,7], and Cs [8–10]. In most cases, rate constants on the order of 10^{-11} cm^{3}s^{-1} were measured at temperatures around 100 μK. In our previous work on ^{85}Rb and ^{87}Rb [6,7], we measured the ΔF collision rate by observing a large jump in the rate of trap-loss collisions when the trap intensity (and therefore the trap depth) was lowered below a critical value. At even lower intensities, the collision rate appeared to level off, indicating that all ΔF collisions were leading to escape. These previous measurements were performed with the MOT in continual operation, so that the effects of laser light (total intensity < 2 mW/cm^2) were always present. In the current experiment, we modulate the lasers and manipulate the ground-state population in order to measure separately the ΔF collision rates in the presence and absence of trap laser light, i.e., in the light and in the dark.

Meanwhile, experiments [11] with overlapping ^{87}Rb BECs of mixed spin states, $|F = 2, m_F = 2>$ and $|F = 1, m_F = -1>$, showed a surprisingly small spin-exchange collision rate: $2.2(9) \times 10^{-14}$cm^{3}s^{-1} for $T < 1\ \mu$K. Subsequent theoretical analyses [12–14] concluded that this anomaly could only be attributed to a near coincidence in the s-wave scattering lengths for these two states. This in turn constrains the ground-state potentials. Using the best potential from Ref. [12], we calculate ^{87}Rb ΔF collision rates that are well below the previous measured values [6,7]. One possible explanation for this discrepancy is that the ground-state collisions are enhanced by the laser light of the MOT. In the current experiment we both verify the presence of such an enhancement and eliminate these enhancement effects by

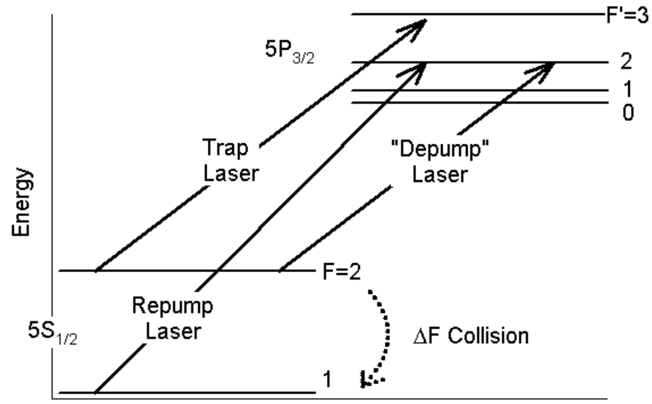

FIG. 1. Energy levels of ^{87}Rb used in the population switching. The trap operates on the $F = 2 \rightarrow F' = 3$ transition, while the repumper is tuned to the $F = 1 \rightarrow F' = 2$ transition. The depumper drives the $F = 2 \rightarrow F' = 2$ transition, which depopulates the $F = 2$ level.

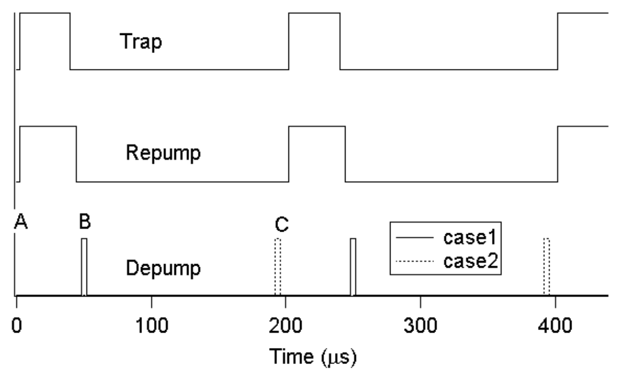

FIG. 2. Timing diagram for the experiment. The trap and repumper lasers are on for t_{AB}, followed by a dark period t_{BC}. The depumper laser is pulsed on to transfer atoms from $F = 2$ to $F = 1$. In case 1 (solid line), this occurs at B, so that no ΔF collisions can occur during the dark period. In case 2 (dotted line), this occurs at C, allowing ΔF collisions to occur in the dark.

performing the measurements in the dark. We thereby measure the true ground-state ΔF collision rate. We also recalculate the hyperfine-changing collision rate based on potentials that are constrained by more recent experiments [11,15–17]. These calculations and the current experimental data show significantly improved agreement, especially at collision temperatures below 100 μK.

The key aspect of the current experiment is the use of a population switching technique to compare trap-loss collisional rates when both atoms are in the upper ($F = 2$) vs. lower ($F = 1$) hyperfine levels of the ground state. Since ΔF collisions occur for $F = 2$ atoms, but not for $F = 1$ atoms, the difference in these collisional rates yields the ΔF collisional rate. Normal operation of the MOT requires near-resonant laser light and for the atoms to be in the $F = 2$ level, so we alternate periods of trapping (and cooling) with periods of darkness. We set the population at the beginning of the dark phase, thereby controlling whether or not ΔF collisions will occur.

Details of the experimental setup have been described previously [7]. We operate the trap at a detuning of -1Γ ($\Gamma/2\pi = 5.89$ MHz) relative to the $5S_{1/2}(F = 2) \rightarrow 5P_{3/2}(F' = 3)$ transition and at a sufficiently low time-averaged intensity (sum of all six beams = 1.5 mW/cm^2) that the products of a ΔF collision can escape. The axial magnetic field gradient is 0.48 mT/cm and the Gaussian trap laser beams have a $1/e^2$ diameter of 6.3 mm. The trapped clouds are Gaussian with typical $1/e$ diameters of $150 - 300$ μm. The repumping laser, which prevents atoms from accumulating in the $F = 1$ level, is tuned to the $(F = 1) \rightarrow (F' = 2)$ transition, its intensity fixed at ~ 3 mW/cm^2. As shown in Fig. 1, a separate depumping beam (~ 10 mW/cm^2), tuned to the $(F = 2) \rightarrow (F' = 2)$ transition, serves to rapidly transfer atoms from $F = 2$ into $F = 1$.

The timing sequence is shown in Fig. 2. All switching is performed with acousto-optic modulators with acoustic (rf) and optical extinction ratios of > 50 dB and > 30 dB, respectively. The trap and repumper lasers are left on for a variable time, with the repumper turning off slightly after the trap to ensure that all of the atoms are in the $F = 2$ level at the start of the dark period. In case 1, the ~ 2 μs depumper pulse occurs immediately after the trap and repumper turn off, thereby preventing any ΔF collisions from occuring during the dark period t_{BC}. In case 2, the depumper pulse occurs just before the trap and repumper turn back on, thereby allowing ΔF collisions to take place in the dark. The presence of this pulse in case 2 ensures that the difference in collisional rates for the two cases will not be affected by differences in the trapped sample (e.g., fluorescence or pushing from the depumper). The depumping is not sensitive to the details of the pulse since the transfer requires only a few spontaneous emissions.

The temperature of the trapped atoms is varied by changing the trap laser intensity. We keep the time-averaged trap intensity constant to maintain a nearly constant trap depth, thereby ensuring that ΔF collisions lead to escape [18]. Thus, the duty cycle for the trap laser is decreased from 50% to 10% as its intensity is increased from 3 mW/cm^2 to 15 mW/cm^2. This range of intensities provides a variation in temperature from ~ 60 μK to ~ 130 μK, as measured by time-of-flight in our previous work [19]. We keep the repetition period fixed at 200 μs.

After the MOT is loaded from a chirp-cooled beam, it is allowed to decay while its fluorescence is monitored.

The ultracold collisional rate constants are obtained by analyzing the decay curves and extracting the two-body decay rate β due to inelastic collisions within the trap. Since we follow each decay for ~ 100 s, the two cases are alternated from one decay to the next in order to reduce the effects of slow drifts of trap parameters. The statistical variation of β for fixed trap parameters is typically $< 5\%$, allowing us to extract small differences between the two cases. The statistical uncertainties in relative values of β for different trap parameters, as indicated by the error bars in Fig. 3, are determined primarily by uncertainties in trap volume. The absolute scale for β is known to within $\sim 20\%$ due mainly to uncertainties in the overall calibration of atom number [7]. All quoted uncertainties are one estimated standard deviation (combined standard uncertainty).

The rate constant for ΔF collisions in the dark is $\beta_{dark} = (\beta_2 - \beta_1)/\eta$, where $\eta = t_{BC}/t_{AC}$, which varies from 50% to 90%, is the fraction of time the atoms spend in the dark (see Fig. 2). The rate constant for ΔF collisions in the presence of the trap laser is $\beta_{light} = \beta_1/(1-\eta)$. These quantities are plotted as a function of temperature in Fig. 3. Two conclusions are immediately obvious from the data. First, the laser light dramatically increases the ΔF collision rate by up to a factor of ~ 30. There are several possible mechanisms for this enhancement. The trap laser can excite a pair of ground-state atoms at long range, after which the atoms may be accelerated and deflected towards each other before spontaneous emission occurs. This may result in an enhancement of the ground-state collisional flux at short range. Not only is the flux concentrated, but the collisional energy at short range is also increased as a result of the acceleration. This type of flux enhancement has been observed previously [20–25] in other types of collisions. Another possibility is that the collisions directly involve long-range (R^{-3}) excited state potentials. For example, a $1 \times \Delta F$ collision could involve an excited atom: $5S_{1/2}(F=2) + 5P_{3/2} \rightarrow 5S_{1/2}(F=1) + 5P_{3/2}$. Radiative escape could also occur, where the excited atom emits a less energetic photon than it absorbed, converting the remainder into kinetic energy which exceeds the trap depth. However, extrapolating previous measurements [6,7] of ground-excited collisional rates to our low laser intensities yields rates which are several orders of magnitude smaller than the present measurements. Larger than expected ^{87}Rb ΔF collision rates in the presence of laser light have also been observed in an independent experiment [26].

Concentrating now on β_{dark}, the second conclusion we draw from Fig. 3 is that the agreement between experiment and theory is markedly improved by using potentials constrained by a number of recent experiments, as described below. A theoretical calculation based on the potentials [12] constrained by only the original mixed-spin BEC experiment [11] predicts rates at even the highest temperatures that are $< 8\times10^{-13}$ cm^{3}s^{-1}, well below the present measurements. Despite this overall improvement, the measurements of β_{dark} appear to show a much stronger energy dependence than predicted by the theory. Theory is unable to fit the highest temperature data point and can only fit the lower temperatures for select choices of the singlet and triplet scattering lengths.

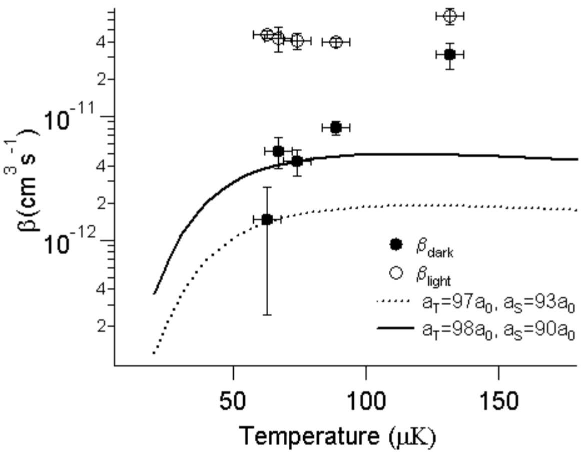

FIG. 3. Trap-loss collisional rate constants β vs. atomic temperature. β_{dark} (solid symbols) and β_{light} (open symbols) are the rate constants for ΔF collisions occuring in the absence and presence of laser light, respectively. The theoretical predictions for β_{dark} for two different values of the singlet and triplet scattering lengths a_T and a_S are shown as the solid and dashed lines.

The theory is based on a set of standard close coupling equations [12,27,28] and includes partial waves from $l = 0$ to 4. Two major types of interactions lead to ΔF collisions: exchange scattering and the much smaller spin-spin dipole interactions. The latter process is enhanced in the heavier alkalis [27] due to second order spin-orbit interactions which mimic the effect of the spin-spin dipole interaction. However, in Rb the rate due to the second order spin-orbit interaction effectively cancels that from the normal spin-spin dipole interaction, diminishing the overall rate for this process. The exchange process is also reduced in ^{87}Rb as a result of nearly identical s-wave scattering lengths for the $|F=2, m_F=2>$ and $|F=1, m_F=-1>$ states [12–14]. This coincidence allowed for the original formation of ^{87}Rb mixed-spin BECs [11] and led to additional two-component BEC experiments using the $|F=2, m_F=1>$ and $|F=1, m_F=-1>$ states [16].

More recently, the last bound state of $^{87}Rb_2$ correlating to two $|F=1, m_F=-1>$ atoms has been determined by photoassociative spectroscopy [15], and a Feshbach resonance in ^{85}Rb has been measured [17]. Combining these results with the constraints imposed by the two-component BEC experiments [11,16], we obtain new potentials. Consistency between all of these experiments provides severe constraints between the number of bound vibrational levels in the $a^3\Sigma_u$ and $X^1\Sigma_g$ potentials and the value of C_6 [29]. A preliminary analysis of this combined data set yields for ^{87}Rb a triplet scattering length $a_T = 98 \pm 2\ a_0$ ($1\ a_0 = 0.0529177249$ nm) and a singlet scattering length $a_S = 90 \pm 4\ a_0$. The calculated ΔF collision rate using these potentials is shown as the solid line in Fig. 3. The dotted line in Fig. 3 is a calculation based on potentials where the constraint imposed by the ^{85}Rb Feshbach resonance is removed. This biases the analysis toward a larger singlet and a smaller triplet scattering length, although the values are still within the quoted uncertainties.

Although the agreement between theory and experiment has improved for temperatures $< 100\ \mu$K, the calculations show a much weaker thermal dependence than found in the experiment. This discrepancy is puzzling since the theory is now very tightly constrained by the mixed-state BEC measurements [11,16], the ^{85}Rb Feshbach experiment [17], and spectroscopic measurements [15]. Reasons for this discrepancy are not clear, but we mention the following possibilities. Although the MOT lasers are off, there may possibly be a residual correlation of spins on the spatial scale of the trapped cloud. The calculations assume equally populated m_F states. However, even in the most correlated case, with all collisions involving atoms in the same m_F state, the largest possible predicted rate is less than a factor of 2 higher than the curves in Fig. 3. Another possibility is that the depumping pulse heats the atoms so that the temperature is increased in the dark. However, the recoil energy from the few excitation cycles required for population transfer is negligible compared to the starting temperatures of $\sim 100\ \mu$K.

In summary, we have measured the rate of ^{87}Rb hyperfine-changing collisions in a MOT, both in the dark and in the presence of trapping light. We draw two main conclusions. First, there is a very large enhancement in this ground-state collision rate caused by the relatively weak trapping laser. Previous experiments [6,7] failed to account for this enhancement, leading to a dramatic discrepancy with theory. Second, we compare our measured collision rates in the dark with theoretical predictions and find them to be consistent at all but the highest temperature. These predictions are based on a new analysis of recent ^{87}Rb [11,15,16] and ^{85}Rb [17] experiments which yields triplet and singlet scattering lengths for ^{87}Rb of $a_T = 98 \pm 2\ a_0$ and $a_S = 90 \pm 4\ a_0$. Calculations based solely on the low spin-exchange rates measured in the original mixed-BEC experiments [11] match our data rather poorly. Further work, both experimental and theoretical, aimed at understanding the temperature dependence is clearly called for. In particular, collisional measurements over a wider temperature range and for both ^{85}Rb and ^{87}Rb would be useful. The role of laser enhancement in ground-state collisions of other species remains an open question.

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