Isotopic Difference in Trap Loss Collisions of Laser Cooled Rubidium Atoms

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We report measurements of collisional rate constants for cold Rb atoms held in a magneto-optical trap. ^{85}Rb and ^{87}Rb display significantly different behavior. At low trap laser intensities, atoms which undergo a hyperfine-changing collision gain sufficient velocity to escape the trap. Since the hyperfine splittings are quite different for the isotopes, the loss rates display a large isotopic dependence in this regime. At higher trap laser intensities, where trap loss is due to inelastic collisions involving excited atoms, a dramatic and unexpected isotopic dependence is seen. Under identical conditions, the loss rate for ^{85}Rb is 3.3 times that of ^{87}Rb.

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The techniques of laser cooling and trapping have opened the door for studies of atomic collisions in the millikelvin temperature range. Several novel features arise in this very low energy regime. Since the kinetic energy is small, weakly attractive long-range potentials play a dominant role. The combination of this increased length scale and the reduced collisional velocity results in a considerably lengthened collision duration. It is thus possible for spontaneous emission to occur during the collision, with dramatic consequences for collisions involving excited atoms. In addition to their intrinsic interest, such collisions are important since they impede efforts to achieve high densities of trapped atoms and to perform precision experiments with them.

To date, experiments with cold atoms have investigated associative ionization (AI) in sodium [1,2] and trap loss collisions (TLC) in sodium [3] and cesium [4]. The AI experiments have shown a dramatic dependence [2] of the rate constant on laser intensity and frequency which has been interpreted [5] in terms of the interplay between light shifts and molecular potentials, with molecular bound-state resonances also playing an important role. The TLC measurements in sodium [3] displayed a surprising independence of the trap loss rate on laser intensity. Analogous work in cesium [4] demonstrated a loss rate which increased with laser intensity, consistent with the idea [6] that such collisions involve a ground-state and an excited-state atom interacting via the long-range r^{-3} resonant dipole interaction. Use of a separate "catalysis" laser to enhance the collision rate strongly supported this picture.

In this Letter, we present experimental results for TLC in rubidium. The existence of two stable isotopes provides us with a unique variable in the study of these cold collisions. The two isotopes, ^{85}Rb and ^{87}Rb, differ only slightly in their mass, but more importantly in their hyperfine structure (see Fig. 1). Since their cooling and trapping processes are very similar, any differences in trap loss reflect a difference in their collisional properties. We have seen two such differences; one is expected, the other is not. At low trap laser intensities, the trap depth is sufficiently small that inelastic hyperfine-changing collisions result in escape [4]. Since the ground-state hyperfine splittings are markedly different for the two isotopes, it is expected, and confirmed by our measurements, that the trap loss rate should exhibit an isotopic dependence in this regime. At high trap laser intensities, the trap loss is due to inelastic collisions between a ground-state and an excited-state atom. The kinetic energy given to the atoms is thought to result either from a change in fine-structure state or from radiative redistribution [6,7]. We observe a large difference (a factor of 3.3) between the isotopes, suggesting the possible importance of excited-state hyperfine structure on the long-range dynamics of the collision [8].

Our experimental arrangement is similar to that used by Sesko *et al.* [4] to study TLC in Cs. We use a magneto-optical trap [9] to capture, cool, and confine the Rb atoms. Three orthogonal pairs of counterpropagating laser beams intersect in the center of a quadrupole magnetic field. These beams are Gaussian with a $1/e^2$ diameter of 6.3 mm and opposing beams are oppositely circularly polarized. The trap laser is linewidth narrowed and

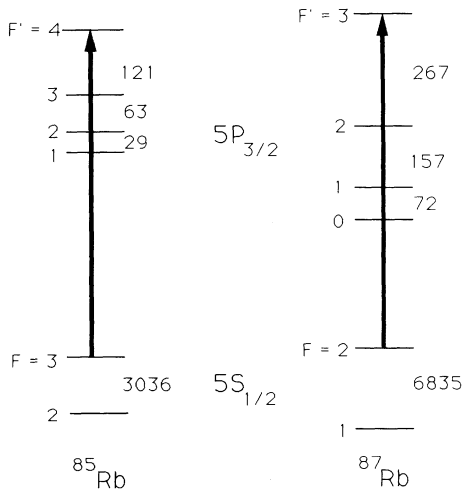

FIG. 1. Hyperfine structure (not to scale) for the $5S_{1/2}$ and $5P_{3/2}$ levels of ^{85}Rb and ^{87}Rb. Energy splittings are in MHz. Arrows indicate the transitions driven by the trap laser.

long-term stabilized to better than 100 kHz by combined optical and electronic feedback [10]. For most experiments described here, this laser is tuned approximately one linewidth (5.9 MHz) below the $5S_{1/2} \rightarrow 5P_{3/2}$ cycling transition ($\lambda = 780$ nm). This cycling transition is $F=3 \rightarrow F'=4$ for ^{85}Rb and $F=2 \rightarrow F'=3$ for ^{87}Rb (see Fig. 1). A separate "repumping" laser is combined with the trap beams to prevent optical pumping into the other ground-state hyperfine level. This repumping laser is free running (linewidth ~ 30 MHz) and is modulated by roughly 40 MHz at a 1-kHz rate. The required magnetic field is produced by two coils arranged in the Helmholtz configuration but with opposite currents. Axial and radial field gradients are 4.8 and 2.4 G/cm, respectively. A separate set of nulling coils allows cancellation of stray fields to ensure that zero field occurs at the center of the trap coils. The trap is loaded with an atomic beam which is slowed by a frequency chirped diode laser [11] tuned to the appropriate cycling transition. A synchronously chirped repumping laser prevents optical pumping during the slowing process.

In order to obtain accurate values for collisional rate constants, we must carefully determine the density of trapped atoms. This involves measuring the size of the trapped atom cloud and the absolute number of trapped atoms. The size is measured by digitizing the image from a charge-coupled-device camera which has a resolution of 50 μm. Atoms in a harmonic potential with a Maxwell-Boltzmann distribution of energies have a Gaussian density profile. The observed profiles are indeed Gaussian with $1/e$ diameters ranging from ~ 200 to ~ 500 μm. As the trap laser intensity is decreased (at a fixed detuning), the trap dimensions are relatively constant until approximately 2 mW/cm^2 (total intensity), at which point the trap begins to expand. The two isotopes behave almost identically except at the very lowest intensities where the ^{85}Rb trap is somewhat larger.

The total number of atoms is obtained by combining measurements of the absorption of a weak resonant probe beam (with trap beams on), excited-state fraction, and trap size. The excited-state fraction is determined by observing photoionization from the $5P_{3/2}$ state with 413-nm light from a krypton ion laser [12]. As the trap laser intensity is increased, the excited-state fraction saturates, and a fit of the photoionization signal to a saturation curve allows us to predict the excited-state fraction at any intensity. These fractions agree very well with values calculated based on the measured trap laser intensities and detunings, assuming an average saturation intensity for a ground-state population equally distributed among the various m_F states. As an additional check on the number of atoms, we measure the trap fluorescence with a calibrated light collection and detection system and combine this information with the excited-state fraction. These complimentary methods give the same result to within 20%.

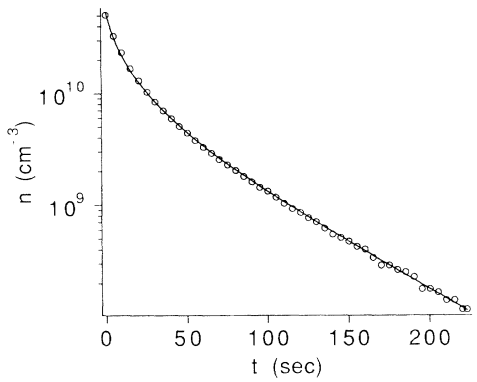

FIG. 2. Decay of ^{87}Rb atoms from the trap for a total intensity $I_t = 1.8$ mW/cm^2 and a detuning $\Delta/2\pi = -4.9$ MHz. The solid line is a fit by Eq. (1) with $\Gamma = 0.020$ s^{-1} and $\beta = 5.8 \times 10^{-12}$ cm^{3}s^{-1}.

The TLC rate constant is determined by monitoring the decay of atoms from the trap [3,4]. There are two contributions to this decay: (1) Background gas molecules (at room temperature) collide with and eject trapped atoms at a rate Γ which is determined by the background gas density [13]. (2) Inelastic (exoergic) collisions between trapped atoms can impart enough kinetic energy to allow the atoms to escape the trap. The rate of these two-body collisions increases quadratically with the trapped atom density n and is characterized by the trap loss rate constant β. Note that β accounts for the fact that two atoms escape the trap for each collision. The time dependence of n is given by

$$\frac{dn}{dt} = -\Gamma n - \beta n^2 . \qquad (1)$$

Since we actually monitor the total number of trapped atoms, we must account for the fact that the density has a Gaussian distribution.

A typical trap decay and the corresponding fit by Eq. (1) are shown in Fig. 2. For all our data, we operate at sufficiently low densities ($n < 2 \times 10^{10}$ cm^{-3}) that radiation trapping effects [14] can be ignored. This is verified by the quality of the fit by Eq. (1) and by a constant trap shape and size during the decay. For most of our data, Γ is relatively constant at a value of 0.02 s^{-1}, fixed by our background pressure of 10^{-10} Torr.

Obviously, our main interest is in the variation of the TLC rate constant β. In Fig. 3, we plot β as a function of total trap intensity at a fixed detuning of -4.9 MHz. Data for both isotopes are shown. The overall trend is similar to that seen in Cs [4] but our values for Rb are consistently lower. At high intensities, β increases with intensity, indicating that collisions involving excited atoms are important. At low intensities, the TLC rate constant jumps up sharply, consistent with ground-state hyperfine-changing collisions providing sufficient kinetic energy to escape the relatively shallow trap. The main

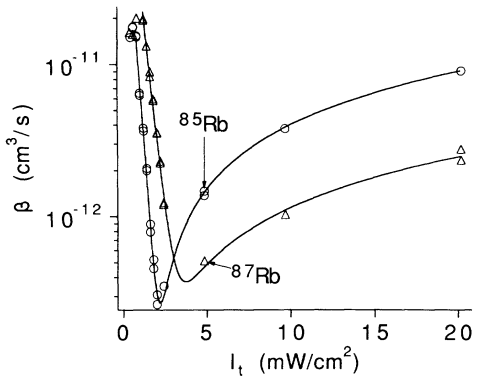

FIG. 3. Dependence of β on total intensity I_t for the two isotopes. The solid lines are curves to guide the eye.

point of this Letter is that although the two isotopes show the same general trend, they differ significantly in each regime.

As pointed out by Sesko *et al.* [4], well-aligned and spatially filtered trap beams are necessary to obtain reproducible values of β. Otherwise, the trap is sufficiently "leaky" that the rapidly occurring hyperfine-changing collisions can dominate the trap loss at all intensities. Since we switch between isotopes by simply tuning the lasers, we can be quite confident that beam quality, alignment, and magnetic fields are identical for all measurements within a given run. Thus, relative values of β within a run (e.g., Fig. 3) can be compared at the 20% level, while absolute values are accurate (based on variations between runs) to $\pm 40\%$, with the error dominated by the trap size measurements.

Concentrating first on the data at higher intensities, we note that both isotopes display a linear dependence of β on intensity. However, the value of β for ^{85}Rb is always a factor of $3.3(\pm 0.3)$ larger than that for ^{87}Rb. This dependence is totally unanticipated by current theories [6,7]. The only important difference between the two isotopes is their hyperfine structure. Ground- and excited-state splittings in ^{85}Rb are less than half the analogous splittings in ^{87}Rb (see Fig. 1). The effects of hyperfine structure on the long-range interactions of two colliding atoms are apparently quite important.

We can compare our absolute TLC rate constant to a theoretical prediction [7] at a total trap intensity of 10 mW/cm^2. Our measured value for ^{85}Rb is $\beta = 3.4 \times 10^{-12}$ cm^{-3}s^{-1} (average between two runs), while the theory predicts $\beta = 1.7 \times 10^{-11}$ cm^{-3}s^{-1}. Obviously, the agreement is not very satisfactory. A more recent calculation [15] yields an approximate value $\beta \sim 5 \times 10^{-12}$ cm^{-3}s^{-1}, which appears to agree much better with our data. However, this agreement must be viewed as somewhat fortuitous since the theory does not distinguish between the isotopes, while we measure $\beta = 1.0 \times 10^{-12}$ cm^{-3}s^{-1} for ^{87}Rb under these conditions. Another recent experiment [16] obtains, under the same conditions, a value of β for ^{85}Rb which agrees quite well with ours.

Although the overall behavior of the two isotopes at low intensities is not unexpected, there are several specific features we would like to point out. First, the "critical" intensity at which the TLC rate constant begins to increase is larger for ^{87}Rb than for ^{85}Rb by a factor of ~ 1.5. This same ratio of intensities holds if we compare the two isotopes at the same value of β on the sharply increasing portions of the curves in Fig. 3. This ratio is somewhat surprising since the ratio of kinetic energies released in a hyperfine-changing collision is 2.25. If escape is determined by position-dependent forces (i.e., the static trap potential) and if these forces are proportional to intensity, then the ratio of critical intensities should be the ratio of kinetic energies (i.e., 2.25). If, on the other hand, escape is prevented by the velocity-dependent forces associated with the trap, and these forces are proportional to intensity [17], then the ratio of intensities should be the ratio of velocities: 1.48. Our data support this second mechanism. We have also performed three-dimensional rate equation simulations of our trap which include saturation, optical pumping of the various m_F states, and the spatial variations of the laser intensity and magnetic field. If an atom at the center of the trap is given an energy corresponding to a hyperfine-changing collision, these simulations show that the intensity at which escape occurs differs for the two isotopes by a factor of ~ 1.5. All the evidence supports the idea that damping forces are much more important than restoring forces in preventing escape.

A second obvious feature at low trap intensities is the steep but continuous increase in β as the intensity is reduced. The energy gained in a hyperfine-changing collision is well defined, as is the initial location of the atoms in the trap. But the atoms can recoil in any direction and the trap forces (both damping and restoring) are anisotropic due to the different axial and radial magnetic field gradients. Therefore it is not unreasonable to expect a continuous increase in the escape rate as the intensity is lowered. When the rate first starts to increase, escape is allowed in the least damped direction. When the rate levels off, escape is allowed in all directions.

The fact that β does level off at the lowest trap intensities is significant. Since the excited-state fraction is very low in this regime, we can say that this plateau is a true measure of the ground-state hyperfine-changing collision rate. Both isotopes have roughly the same value: $\sim 2 \times 10^{-11}$ cm^{3}s^{-1}. This is in reasonable agreement with recent calculations [18].

As a final observation, we have seen a variation in Γ, the loss rate due to background gas collisions, with the trap intensity, as shown in Fig. 4. At low intensities, Γ increases with decreasing intensity. As the trap intensity is decreased, a lower velocity is required for escape and hence a larger fraction of the background gas collisions contribute. However, this dependence should be rather

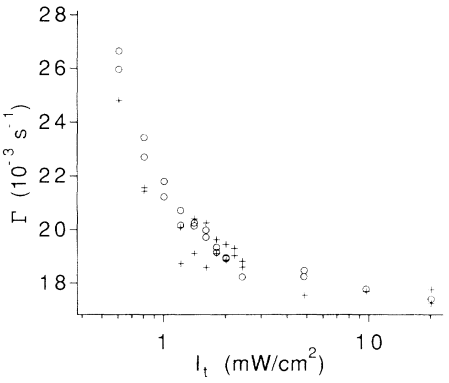

FIG. 4. Dependence of Γ on total intensity I_t for ^{85}Rb (circles) and ^{87}Rb (crosses). Note that the I_t axis is logarithmic.

weak as a result of the rapid decrease of energy transfer at large impact parameters [13]. The fact that Γ does increase significantly thus indicates that the ability of the trap to confine even gently deflected atoms deteriorates quite rapidly at the lowest intensities. This is consistent with our observation that the trap begins to expand at low intensities. This expansion and the increase in Γ are both slightly larger for ^{85}Rb than for ^{87}Rb.

In conclusion, we have compared trap loss collisions for the two isotopes of rubidium. At high trap intensities, where collisions involving ground- and excited-state atoms dominate, we see the predicted increase in trap loss rate with intensity. However, a large and unexpected isotopic difference is seen. At low trap intensities, ground-state hyperfine-changing collisions dominate the trap loss. Our data suggest that it is the velocity, not the energy, which determines whether escape occurs. Since the only significant difference between the isotopes is the hyperfine structure, our work points out that theory must include these effects for accurate predictions.

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